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Ozone Disinfection and Color Removal in Wastewater

Los Angeles County Sanitation Districts
Whittier, CA

Prepared for

Municipal Environmental Research Lab.
Cincinnati, OH

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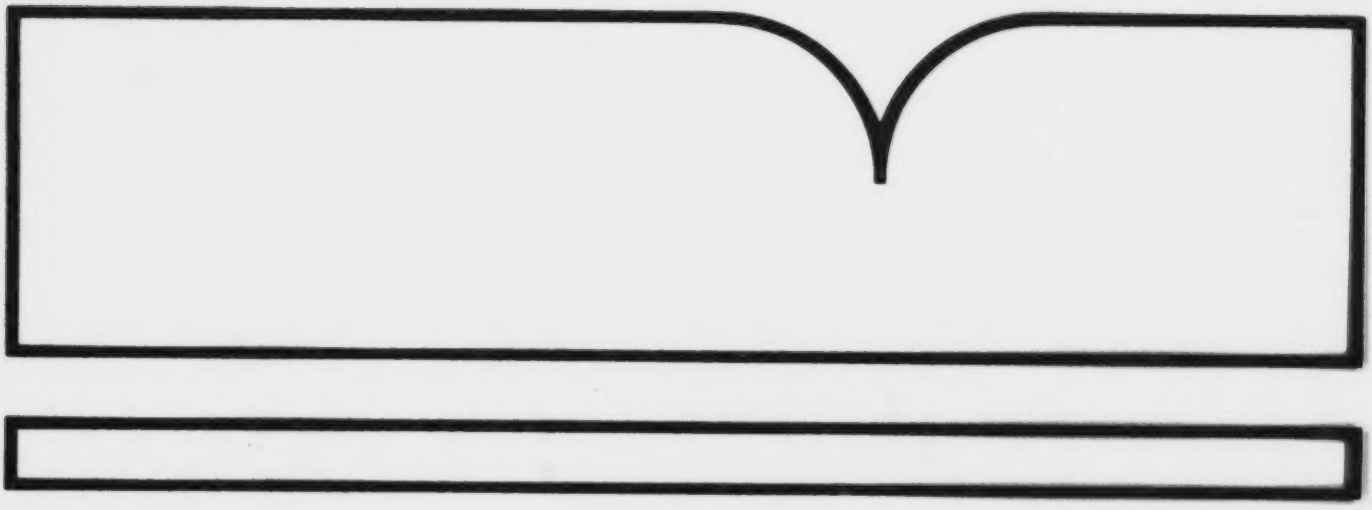

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OZONE DISINFECTION AND COLOR REMOVAL IN WASTEWATER

by

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Contract No. 14-12-150

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16. ABSTRACT

Various ozone contacting systems were evaluated. A sparger incorporated into a six-stage contacting system was found to be the most practical system. Over 80 percent ozone transfer efficiency was obtained in secondary effluent with an applied ozone dosage of 50 mg/l. Despite efficient mass transfer with the system, an ozone consumption in excess of 50 mg/l was found to be necessary to accomplish the disinfection goal of 2.2 MPN/100ml effluent. The color goal of 10 units was achieved at an ozone dose of 10 mg/l. The use of carbon filtration prior to ozonation reduced the ozone dosage required for adequate disinfection to as low as 1 mg/l. Pretreatment of the sand and carbon filters was also briefly investigated No significant advantage was found for these applications.

The effects of various parameters on ozone disinfection efficiency were investigated. The high ozone dosage required to accomplish the disinfection goal of this study was attributed to soluble COD, nitrite, suspended solids, and the color compounds. Effect from contact time was negligible as most disinfection occurred in the initial three minutes of ozone application. The residual ozone concentration in effluents which met the 2.2 or less total coliform MPN per 100 ml limit was much higher in effluent with a relatively high organic content (secondary effluent) than in effluents with a relatively low organic content (carbon effluent).

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

The use of ozone for disinfection and color removal was evaluated as a potential treatment alternative for the Pomona Water Reclamation Plant. This report provides the results of that investigation including the evaluation of several ozone generation and contacting systems with air or oxygen gas feeds.

Francis T. Mayo, Director
Municipal Environmental Research Laboratory

ABSTRACT

The use of ozone for disinfection and color removal was investigated by the County Sanitation Districts of Los Angeles County at its Advanced Wastewater Research Facility in Pomona, California. Partial funding for the project was provided by the Environmental Protection Agency.

The main objective of the study was to evaluate the feasibility of utilizing ozone for disinfection and color removal at the Pomona Water Reclamation Plant. The process was to be evaluated on the basis of the cost of complying with the California effluent coliform limit of 2.2 total coliform MPN per 100 ml and a maximum color goal of 10 units.

In phase 1 of the study, various contacting systems were evaluated. A sparger incorporated into a six-stage contacting system was found to be the most practical system. Over 80 percent ozone transfer efficiency was obtained in secondary effluent with an applied ozone dosage of 50 mg/l. Despite efficient mass transfer with the system, an ozone consumption in excess of 50 mg/l was found to be necessary to accomplish the disinfection goal in secondary effluent. The color goal was achieved at a much lower ozone dose of 10 mg/l. The use of carbon filtration prior to ozonation reduced the ozone dosage required for adequate disinfection to as low as 1 mg/l.

In the pilot phase of the study, the effects of various parameters on ozone disinfection efficiency were investigated. The high ozone dosage required to accomplish the disinfection goal of this study was attributed to soluble COD, nitrite, suspended solids, and the color compounds. Effect from contact time was negligible as most disinfection occurred in the initial three minutes of ozone application. The residual ozone concentration in effluents which met the 2.2 or less total coliform MPN per 100 ml limit was much higher in effluent with a relatively high organic content (secondary effluent) than in effluent with a relatively low organic content (carbon effluent).

Pretreatment of the sand and carbon filters was also briefly investigated. No significant advantage was found for these applications.

Finally, the costs required to meet the expressed goals of the study were estimated to be 12 cents/1000 gallons for disinfection and 6 cents/1000 gallons for color removal based on a typical secondary effluent and 50 percent oxygen recycling.

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CONVERSION TABLE

1 MGD	=	3.785×10^3 m^3/d
1 Psig	=	6.9 K Pa
1 SCFM	=	28.3 L/min
1 gpm	=	3.785 L/min
1 gpm/ft^2	=	0.6750 L/m^2 - Sec
1 $SCFM/ft^2$	=	0.305 $M^3/min - m^2$
1 lb/day	=	454 g/d
1 lb	=	454 g
1 in	=	2.54 cm
1 ft	=	0.305 m
1 ft^3	=	0.0283 m^3

SECTION 1

INTRODUCTION

The use of ozone for wastewater treatment was investigated by the County Sanitation Districts of Los Angeles County at its Advanced Wastewater Treatment Research Facility in Pomona. Various ozone generation and contactors were examined in order to determine the effectiveness of ozone in terms of secondary effluent disinfection and color removal.

Ozone disinfection was investigated by the Sanitation Districts as the result of stringent effluent coliform requirements established by the State of California for reclaimed wastewater. A 7-day median disinfection limit of 2.2 MPN per 100 ml is required for wastewaters discharged to areas where there is possibility of public contact. This disinfection limit requires high chlorine dosages and long chlorine contact periods. Furthermore, in order to protect fish life in receiving waters, the State Department of Fish and Game has restricted the concentration of chlorine which wastewater municipalities can discharge. Consequently, dechlorination is required in most of the Sanitation Districts reclamation plants. The combination of chlorination and dechlorination has elevated the cost of disinfection to a level at which ozone may be an attractive alternative. Hence, the process was investigated as a viable alternative to chlorine.

The removal of color with ozone was of interest to the Sanitation Districts because the City of Pomona was interested in purchasing reclaimed wastewater from the Districts for sale to paper industries within the City. The paper companies had expressed interest in using reclaimed wastewater to replace the potable water used for paper processing provided that the color could be maintained at a level of 10 units or less.

SCOPE OF WORK

The scope of work may be divided into two phases; namely, (a) exploratory (phase 1) and (b) pilot plant (phase 2).

In phase 1, a bench-scale system was constructed to determine the approximate ozone dosage required to meet the State coliform limit and the color requirement for water reuse. This system was later replaced with a large-scale system in order to provide more reliable results.

The pilot plant phase was undertaken to simulate full-scale operation of the ozonation process. The objectives of the pilot plant phase were to gather operation and cost information on the ozonation process and to evaluate the effect of water quality, contact time, and ozone residual on ozone disinfection efficiency.

The systems constructed in this study were also used to examine other applications of ozone. For example, the use of ozone as a substitute for coagulation/flocculation chemicals and as a pretreatment step for carbon filtration were studied.

SECTION 2

CONCLUSIONS

The conclusions of this study may be summarized as follows:

1. Ozone is an effective disinfectant and color removal agent for wastewater treatment. Ozonated secondary effluent is typically of excellent quality with negligible color, suspended solids, turbidity and bacterial numbers.

2. The ozone consumed to meet the State of California effluent coliform limit was approximately 50 mg/l for the Pomona Water Reclamation Plant secondary effluent. Tertiary processes removed impurities that resulted in a reduction of ozone consumption to less than 10 mg/l for the same standard.

3. Ozone demand was found to be exhibited by soluble COD, suspended solids, nitrites, and color in the Pomona Water Reclamation Plant effluent.

4. The ozone consumed in reducing secondary effluent color to 10 units was 10 mg/l. Pretreatment with tertiary processes marginally reduced the amount of ozone consumed in meeting the same standard.

5. A multi-stage contact system provided better ozone mass transfer than a single-stage contact system.

6. All of the ozone contactors evaluated provided ozone mass transfer efficiencies of greater than 80 percent in secondary effluent when adapted to a multi-stage contact system.

7. The contact time necessary to meet California effluent coliform standards was generally less than three minutes.

8. The effect of residual ozone concentration on disinfection was found to vary with the type of effluent used. Wastewaters of high organic content (secondary effluent) generally required a higher ozone residual than wastewater of low organic content (carbon filter effluent) to achieve the same bacterial reduction. Obtaining a high ozone residual in secondary effluent was difficult whereas a high ozone residual was obtained in a tertiary effluent with minimum applied ozone.

9. Carbon filtration was found to be the most cost-effective pretreatment for disinfection of wastewater with ozone.

10. The application of ozone prior to sand filtration or carbon filtration had little effect on the process performance in terms of COD removal efficiency. However, in terms of color reduction and the deferment of headloss buildup, pre-ozonation was effective.

11. The cost of utilizing ozone to comply with the California effluent coliform limit of 2.2 MPN per 100 ml and reduce secondary effluent color to 10 units was estimated to be 12 cents/1000 gallons and 6 cents/1000 gallons, respectively.

SECTION 3

RECOMMENDATIONS

Ozone has been shown to be an effective disinfectant and color removal agent for wastewater treatment. Therefore, steps which can increase the effectiveness or reduce the operating cost of wastewater effluent ozonation should be pursued. These include:

- Investigation of the use of ozone prior to carbon filtration in order to ascertain the unit cost required to affect a given reduction in color and/or filter backwash frequency. The analysis should include credit for reduced backwash and final disinfection costs.

- Evaluation of full-scale operating costs utilizing various oxygen recycling systems.

SECTION 4

MATERIALS AND METHODS

LOCATION

The pilot plant for the ozonation study was located at the Advanced Wastewater Research Facility in Pomona, California. This facility also houses other pilot scale processes such as carbon filters, sand filters, nitrification reactors, physical-chemical treatment units and chlorination/dechlorination units. Adjoining the research facility is the Pomona Water Reclamation Plant; a 10 MGD activated sludge plant which currently treats approximately 9 million gallons per day. Wastewater entering the plant is primarily domestic in origin with some industrial discharges from surrounding communities. These industries were generally paper and textile companies. Figure 1 shows a plan view of the research facility and the adjoining water reclamation plant.

OZONATION SYSTEMS

Several ozonation systems were examined in phase 1 of the study. Ozonation System No. 1 (Figure 2) contained two single-stage contacting systems, and was constructed in order to enable a brief study of the process. The ozonator was from Ozone Research and Equipment Corporation (OREC) of Phoenix, Arizona (Model Q3B-0). It is a conventional tube design generator which operates at high voltage and utilizes water as coolant for the dielectrics. Rated ozone output of the ozonator was 1 lb/day at two percent by weight concentration in oxygen. The ozone production was varied by either changing the wattage on the ozonator or controlling the oxygen flow. Normal operating pressure and flow for the ozonator were 10 to 20 psig and 0.2 to 0.4 scfm, respectively. The ozone produced was injected into the effluent via the contactors. A teflon membrane sparger was evaluated first followed later in the study by a positive pressure injector (PPI). These devices were provided by OREC and W. R. Grace and Company of Baltimore, Maryland, respectively. Each of the devices was located in a separate chamber and operated independently of each other. The chambers were constructed of PVC material and measured 6.5 inches I.D. and 7.5 feet long. Contact time provided in the chamber was six minutes for a flow of 2 gpm. Off-gases from the contact columns were captured in potassium iodide (KI) solution. In order to increase the concentration driving force of ozone, the direction of feed water was countercurrent to the ozone flow in the sparger system and cocurrent in the PPI system. This was done to achieve better ozone transfer in the effluent as found in the trial studies. Unused ozone from the contacting chambers was removed in gas washing bottles containing potassium iodide (KI) solution.

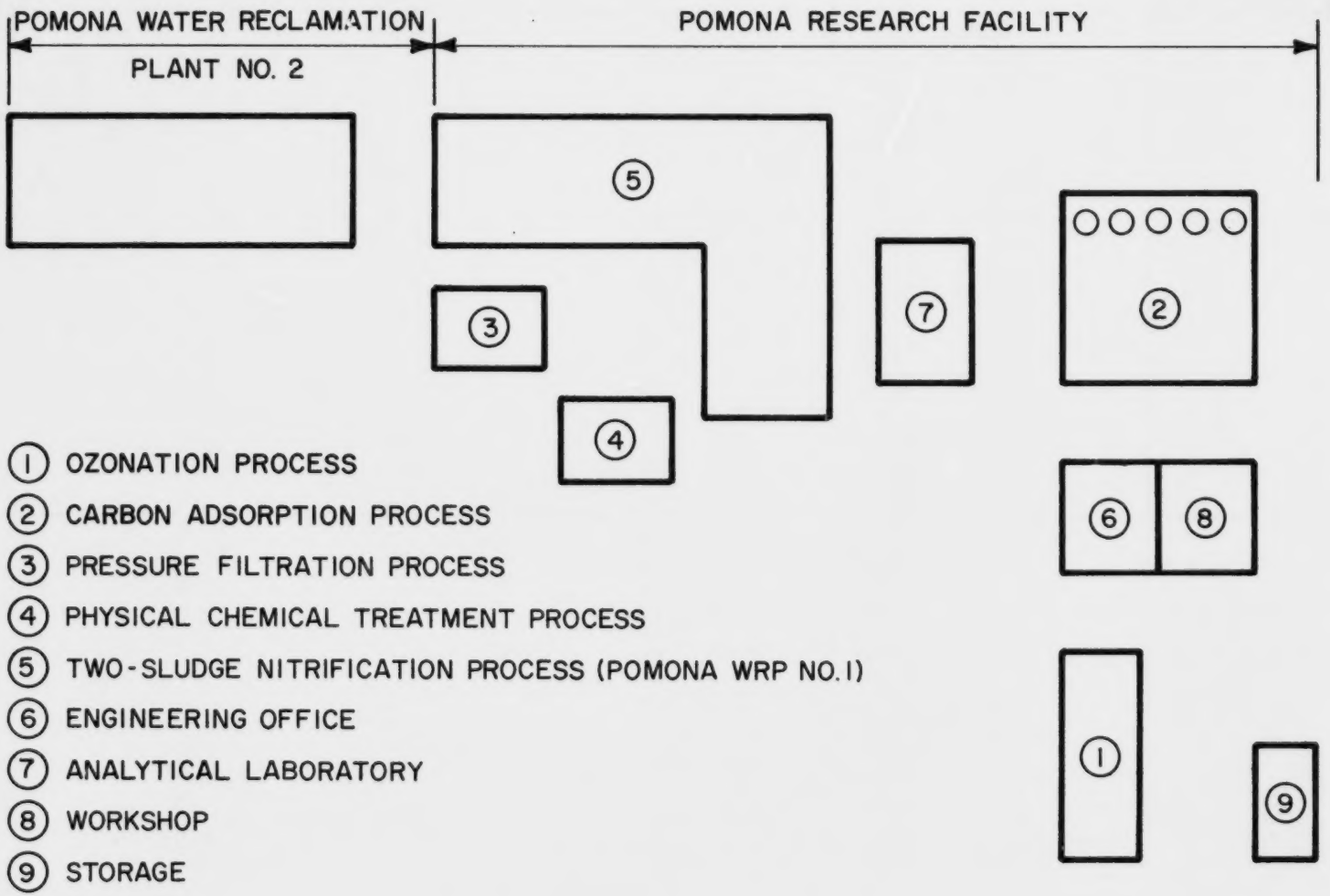


Figure 1 Pomona advanced wastewater treatment research facility.

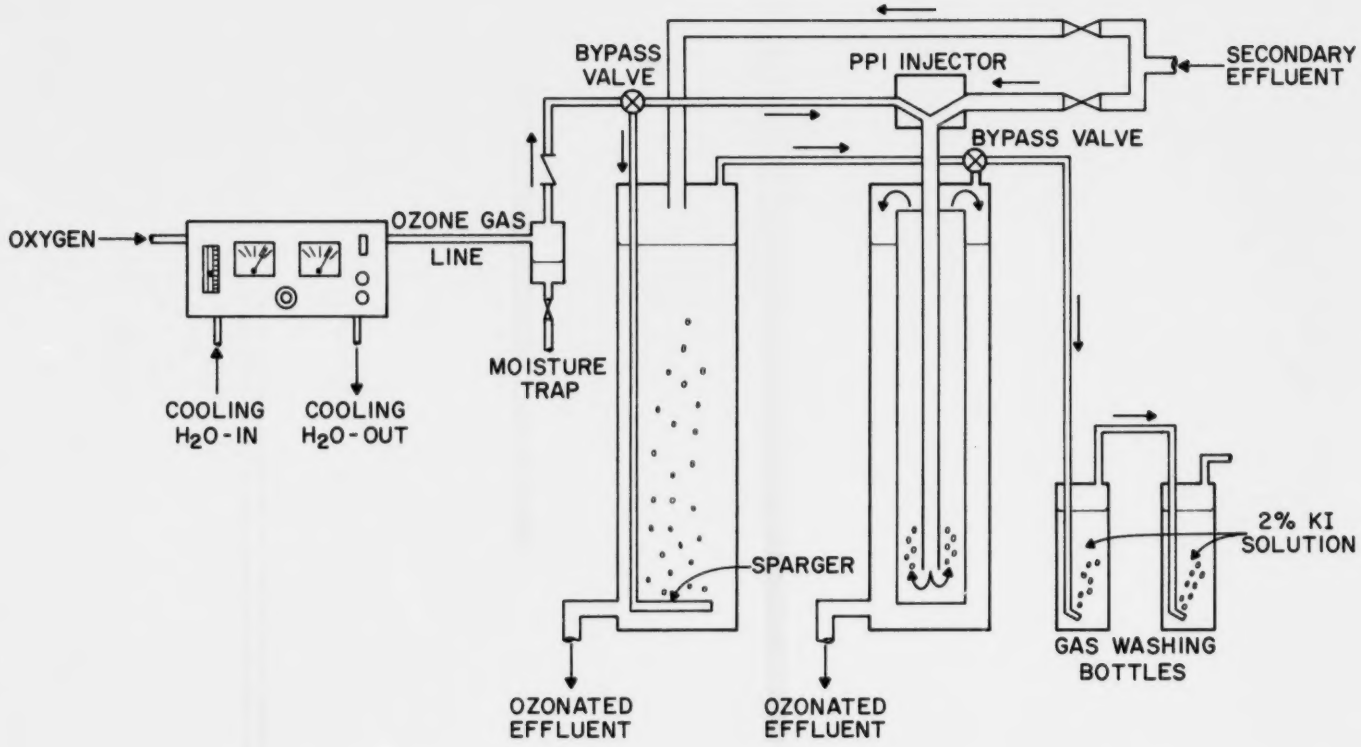


Figure 2 Ozonation System No. 1

Ozonation System No. 2 (Figure 3) was also constructed in phase 1 of the study and was from Purogen, formerly Division of Chromalloy, City of Industry, California. A demonstration by the manufacturer had shown the system to be capable of dissolving high ozone dosages. It was hoped that an improvement in the mass transfer of ozone in secondary effluent would reduce the ozone requirements for disinfection.

The maximum rated ozone output for each of Purogen's ozonators was 1.5 lbs/day at two percent weight concentration in air. The use of oxygen approximately doubles the ozonator's rated output. Ozone from the generator was controlled by adjusting the wattmeter. Normal operating pressure and air flow of the generators were 10 psig and 1 scfm, respectively.

The air was dried to a dewpoint of -40°F by passing it through gas dryers (Model No. 4002-2, Wilkerson Corp., Copiagne, New York). The oxygen was obtained from a 3000 ft^3 liquid oxygen cylinder equipped with vaporizers.

The contact chamber consisted of six contact towers, each measuring six inches I.D. by six feet long, and was constructed of clear plexiglass. The use of this material permitted a visual observation of the effluent during various stages of treatment. The feedwater was fed in series, from the top of each tower through the contact chamber. The ozone could be injected either from the top of the tower to provide cocurrent contact or at the bottom of each tower to provide countercurrent contact with the feedwater. Both directions of flow mixing, according to the manufacturer, provide sufficient mixing to fully utilize the maximum efficiency of its contactors. Off-gas from each tower was injected into the succeeding tower. Ozone in the off-gas from the last tower was absorbed in two percent KI solution.

The ozone solution injected into the contact chamber was prepared by pressuring ozone from the generator into the of feedwater via the Purogen contactor. The gas-liquid ratio for the contactor was 3.6 (liquid flow was 2 gpm) per manufacturer's recommendation. A filter was installed preceding the Purogen contactor to prevent plugging of the contacting device.

Ozonation System No. 3 (Figure 4) was constructed for the pilot plant studies. It was designed to simulate full scale operation and was based on experiences with the preceding two systems. The equipment and method of contacting ozone in wastewater were selected because they were believed to be most suitable for full scale plant operation.

Two PCI, solid state high frequency ozonators were used to generate ozone for the study. Each had a rated ozone output of 10 lbs/day from air or 20 lbs/day from oxygen. The ozone output could be varied manually between 10 and 100 percent of the rated capacity. Delivery pressure and air flow of the ozonators were 15 psig and 5 scfm, respectively. Operating characteristics of the ozonator were 440 volt, 3 phase and 60 Hz.

Unlike the OREC and Purogen ozonators, cooling of the PCI ozonator was accomplished with silicone oil (Dow Chemical 615) in addition to water. The removal of heat from both electrodes and dielectric is necessary for an

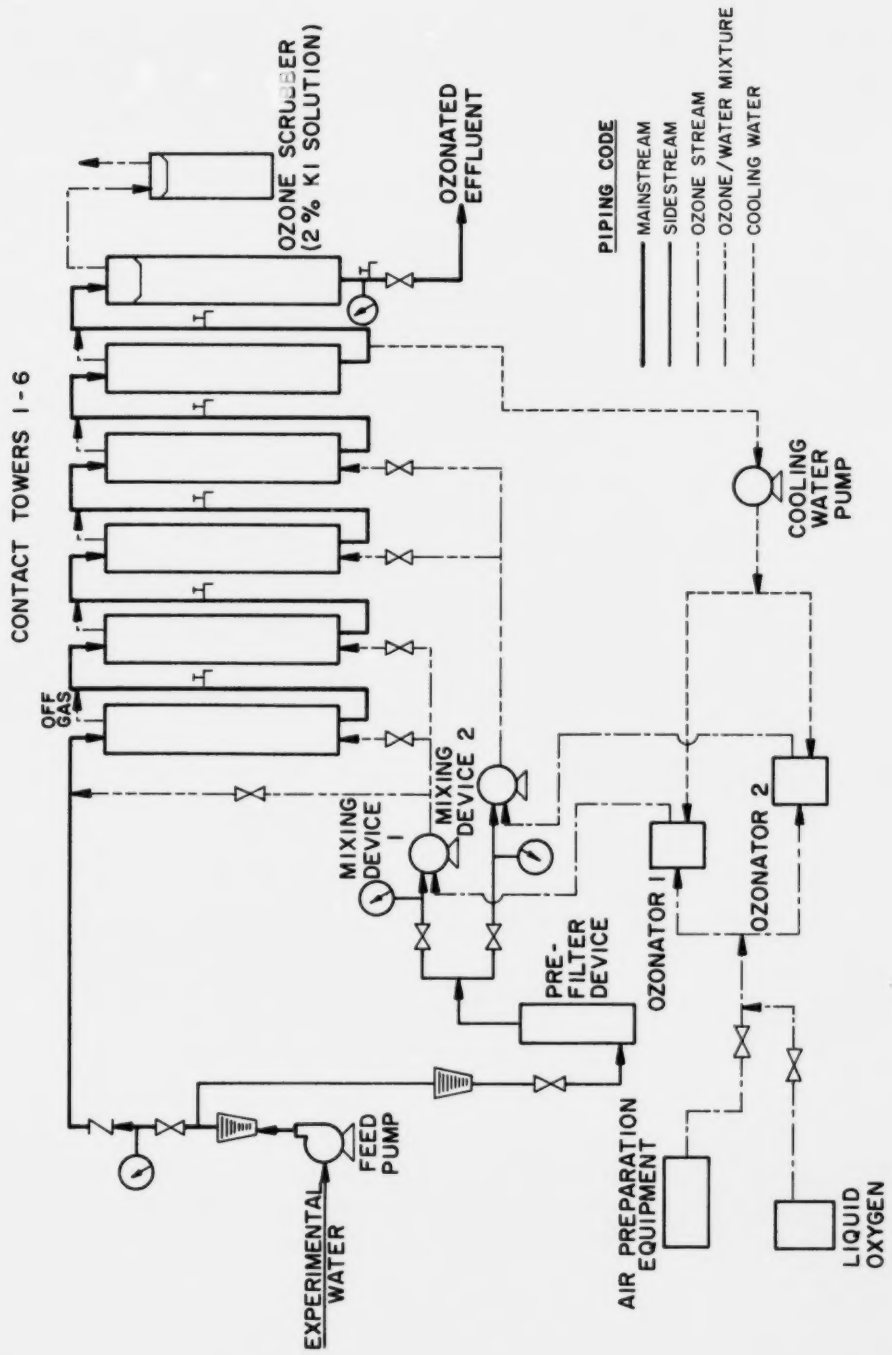


Figure 3 Ozonation System No. 2

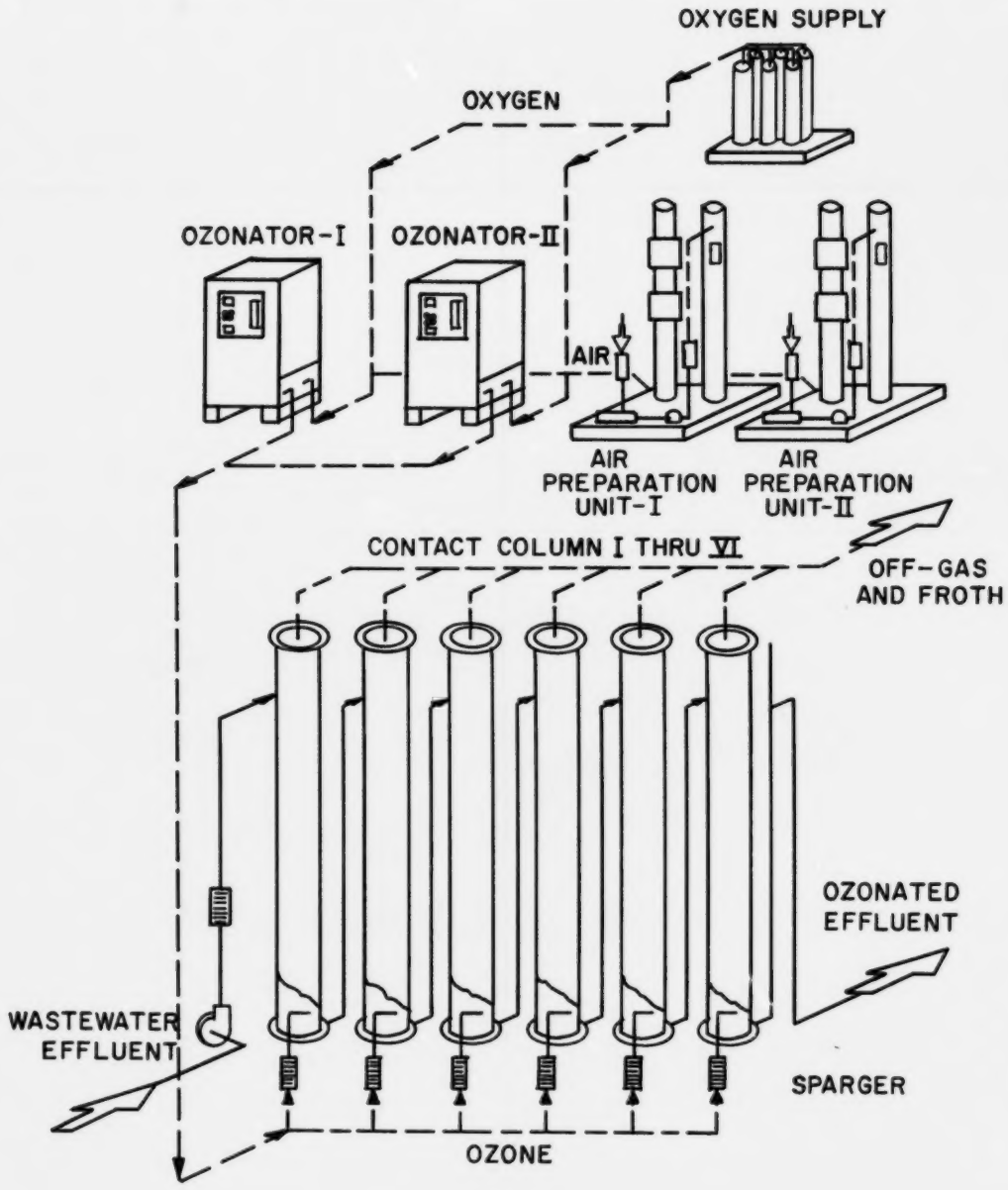


Figure 4 Ozonation System No. 3

efficient production of ozone. Heat removal of the center electrode was accomplished with water. Heat removal of the metal coated electrode and glass was accomplished with silicone oil which was cooled by water in a closed loop heat exchanger.

The ozonators were housed in drip-proof cabinets to protect the high voltage electrical components. Malfunction of the generator was prevented through interlocking devices which deenergizes the ozonator whenever the feed air, cooling water and silicone fluid were low or when the ozone output temperature was high. A main fuse protected the ozonator from excessive current and a switch automatically deenergized the generator whenever the cabinet door was open. These features were critical for equipment protection, especially in full scale operation, and therefore, were incorporated into the pilot plant studies.

Two air preparation units, each connected to an ozonator, were used to supply the air necessary for ozone generation. Figure 5 shows various components of the air drying unit. The unit consisted of a non-lubricated, positive displacement blower with a 2 HP, 3450 RPM motor and inlet silencer (Nash Engineering, Model HK-15), two automatically operated regenerative air drying towers (Kemp Model 50 U), a particle filter (Dollinger No. 23885) and an auxiliary compressor (Gast Model 1HBAB-11M-100X). Each air drying tower was filled with 25 lbs silical gel (grade 03, 3/8 mesh), 25 lbs molecular sieves (type 4A) and 20 lbs aluminum balls (Type T1061). These dessicants were recommended by PCI and produced air with a dew point of -40°F or lower. The use of wet air (dew point of -20°F or higher) impedes the ozone production efficiency and may damage the generator. The regeneration cycle of the air dryer was 8 hours and had been preset by the air drying equipment manufacturer.

The contact chamber consisted of six PVC columns connected in series with each measuring 14 inches in diameter and 18 feet in height. Multiple columns were used to increase ozone transfer efficiency in wastewater. Influent wastewater was fed into the top of the first column and drawn from the bottom of the same column to be fed similarly to succeeding columns. The wastewater effluent was lifted to the head of the first column with a 1 hp centrifugal pump. The flow through the remaining columns was accomplished by gravity. Ozone was fed through diffusers located horizontally at the bottome of each column. The diffusers were cylindrical in shape and were constructed of Type 316 stainless steel with pore size averaging 5 microns. Ozone distribution through the six columns was proportioned by controlling a stainless steel valve and flow meter connected to each diffuser. The off-gas and froth were tapped from the top of each column, passed through a gas-froth separation tank and then disposed into the primary clarifier channel.

TYPES OF EFFLUENT

Several process effluents were evaluated in phase 1 of the disinfection and color removal studies.

Activated sludge secondary effluent was used because disinfection in most of the Sanitation Districts' wastewater treatment facilities is currently applied to this effluent. Two separate activated sludge systems were operated at the Pomona Water Reclamation Plant. One system was operated to obtain a

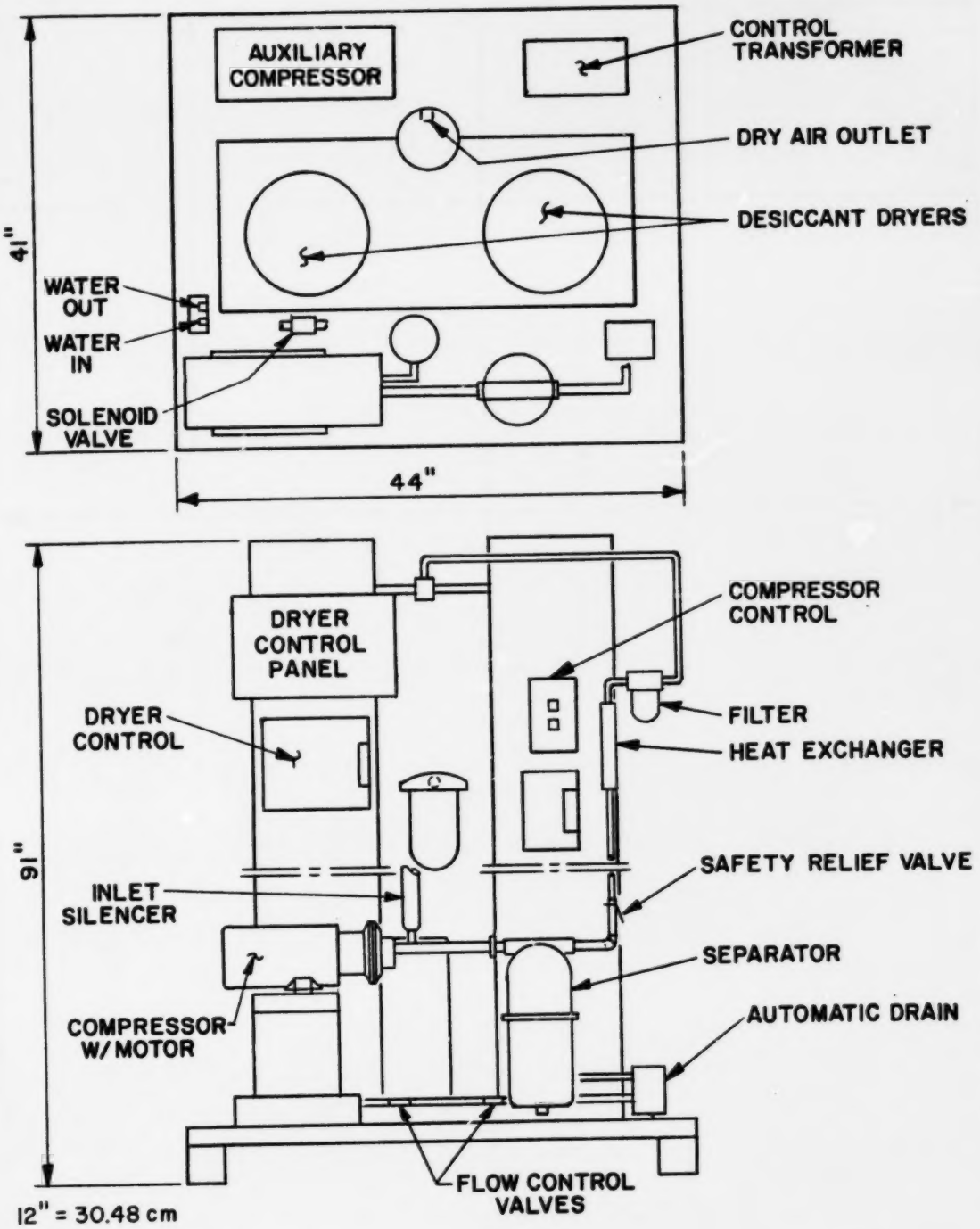


Figure 5 Air preparation unit.

fully nitrified effluent (NH_3-N concentration <2 mg/l). This effluent was used directly as a "feedwater" for the ozone studies. The other activated sludge system produced a more conventional non-nitrified effluent. This non-nitrified effluent was fed to two tertiary pilot plants, namely, an activated carbon filtration system and a sand filtration system. The activated carbon pilot plant was operated at a flow rate of 6 l/sec and consisted of a 1.8 meter bed of granular carbon (8 x 30 mesh) providing an empty-bed detention time of 600 seconds at a loading rate of 3.5 l/sec-m^2. The pressure sand filter operated at a flow of 6700 ml/sec and a hydraulic loading of 3.5 l/sec-m^2. The sand had an effective size of 0.5 mm. Effluents from the two tertiary pilot plants were used as two feedwaters for the ozone studies. In addition, feedwater for the ozonation experiments was also obtained from a pilot scale physical-chemical treatment (PCT) plant. The PCT plant consisted of alum coagulation and sedimentation of raw wastewater (alum dosage of 250 mg/l and polymer dose of 0.3 mg/1), followed by activated carbon treatment (detention time of 1300 seconds).

Table 1 summarizes the quality of the six effluents used in phase 1 of the disinfection studies. The PCT effluent was generally of much higher quality than the other effluents. The tertiary stage activated carbon system was nearing a state of exhaustion at the time of the study which accounts for the relatively high level of COD and color in the effluent from that system. The nitrified effluent was high in suspended solids and turbidity.

In the pilot plant studies, secondary effluent and carbon filter effluent were used. These effluents were similar to those described earlier. The carbon filtered effluent was selected to confirm the findings of phase 1. The reduction of soluble COD by carbon was described as the key to disinfection with ozone at a low dosage. Secondary effluent was used as a comparison for the carbon effluent disinfection responses. In addition, investigations were conducted with two effluents from other tertiary treatment systems operating at the Advanced Wastewater Research Facility in Pomona under a State-sponsored project. These are referred to as Pretreatment Systems A, B, and C. Pretreatment System A is the Title 22 System of the California Administrative Code recommended by the State Department of Health Services to limit waterborne viruses. Pretreatment Systems B and C are proposed by the Sanitation Districts as alternatives to Pretreatment System A.

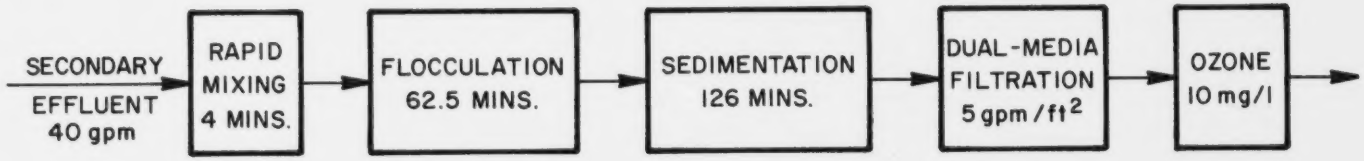
Figure 6 shows a flow diagram of the three pretreatment systems. The flow of secondary and carbon-treated effluents was 50 gpm (72,000 gpd). Flow capacity of the tertiary systems was 25 gpm (36,000 gpd). Table 2 lists the unit dimensions of the pretreatment systems.

Pretreatment System A consisted of coagulation, flocculation, sedimentation and dual-media filtration. Non-nitrified secondary effluent was used for the system. Alum was added to the rapid mix tank at a dosage of 155 mg/l and anionic polymer (Calgon WT-3000) was added to the first flocculation chamber at a dosage of 0.2 mg/l. Filter loading in the experiments was maintained at 5 gpm/ft^2 and backwash was performed once per day. The backwash consisted of an air scour at a rate of 4 scfm/ft^2 for three minutes followed by a water backwash of 20 gpm/ft^2 for five minutes.

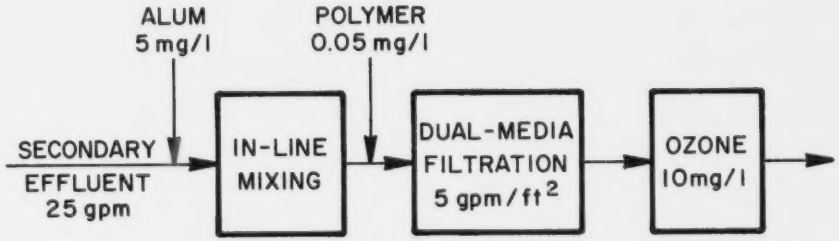
TABLE 1. CHARACTERIZATION OF EXPERIMENTAL WATERS

Parameter	Non-Nitrif. Sec. Effl.	Press. Filt. Sec. Effl.	Two-Sludge Nitrif. Effl.	Press. Filt. Nitrif. Effl.	Carbon Treated Sec. Effl.	PCT Effl.
Color (units)	30	35	31	32	20	2
Turbidity (JTU)	11.2	1.7	38.0	18.0	0.9	3.1
Susp. Solids (mg/l)	9.3	1.8	27.9	12.6	1.2	2.8
Ammonia-N (mg/l)	13.1	17.9	1.9	2.8	10.7	22.1
Nitrite-N (mg/l)	5.1	0.9	1.1	1.0	1.5	0.2
Nitrate-N (mg/l)	0	0.3	6.2	8.5	0.1	4.3
Total COD (mg/l)	37.6	28.6	57.1	50.0	22.0	12.8
Soluble COD (mg/l)	24.4	26.6	27.6	34.6	19.5	10.6
pH	7.2	7.4	7.0	7.1	7.4	6.9
Temp. (^{o}C)	24.0	22.0	24.1	24.0	25.0	22.0

SCHEME A: COAGULATION, SEDIMENTATION, FILTRATION AND OZONATION.



SCHEME B: IN-LINE COAGULATION, FILTRATION AND OZONATION.



SCHEME C: CARBON ADSORPTION AND OZONATION.

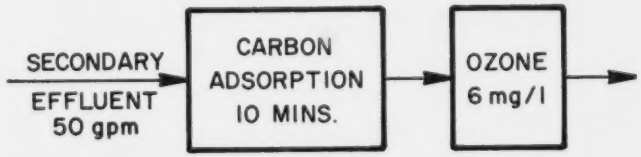


Figure 6 Flow schemes of pretreatment systems.

TABLE 2. CHARACTERIZATION OF VARIOUS PROCESS EFFLUENTS

Case	Effluent	Soluble COD, mg/l	NO_2-N, mg/l	Suspended Solids, mg/l	Total Coliform MPN/100 ml
I	Non-Nitrified Secondary	24.4	5.1	9.3	4.6×10^4 to 1.1×10^5
	Carbon-Filtered	19.5	1.5	1.2	4.9×10^4 to 3.3×10^5
II	Nitrified Secondary	27.6	1.1	27.9	1.7×10^5 to 2.4×10^7
	Filtered Non-Nitrified Secondary	26.6	0.9	1.8	1.7×10^4 to 1.1×10^5
III	Physical-Chemical Treatment	10.6	0.2	2.8	4.9×10^5 to 2.4×10^7
	Filtered Nitrified Secondary	34.6	1.0	12.6	1.7×10^4 to 1.1×10^5

Pretreatment System B consisted of coagulation and dual-media filtration. Alum was added to the rapid mix tank at a dosage of approximately 5 mg/l. The loading rate for the filter was maintained at 5 gpm/ft^2. Anionic polymer (Calgon WT-3000) was injected into the filter influent line at a dosage of from 0.06 to 0.08 mg/l. Backwash procedures for this filter were identical to those employed in System A. The main difference between System A and System B was the elimination of flocculation and sedimentation, the injection of a much lower alum dosage and the addition of polymer for System B.

Pretreatment C consisted of 10 minute carbon contact in a gravity downflow column loaded at 3.5 gpm/ft^2. The carbon used was Calgon Filtrasorb 300.

In the studies of other applications of ozone, the ozonated effluent was produced with Ozonation System No. 2 for the sand filter pretreatment studies and Ozonation System No. 3 for the carbon filter pretreatment studies.

For the sand filter pretreatment studies, Ozonation System No. 2 was used. Two small pressure filters containing sand with each filter measuring 20 inches in diameter and 32 inches in depth were fed with secondary and ozonated effluent, respectively. Both filters operated at a flow of 7 gpm, resulting in a loading rate of 3 gpm/ft^2 in each filter. Detention time in the filter was two minutes. Backwash of the filter was performed once every four days at a rate of 6 gpm/ft^2 for 15 minutes. They were intentionally backwashed less often for purpose of comparing the filter performance. At the above flow rate, the total backwash water volume for each filter was 225 gallons. Filter No. 1 was fed with ozonated secondary effluent and Filter No. 2 was fed with non-ozonated secondary effluent. Results of the two filters with respect to suspended solids, turbidity and headloss were compared.

In the carbon pretreatment studies, the ozonated effluent (dosed with 10 mg/l ozone) was produced with Ozonation System No. 3. Two carbon units, each consisting of two carbon columns connected in series, were employed. One unit was fed with ozonated secondary effluent and the other was fed with non-ozonated secondary effluent. Both pairs of columns were operated simultaneously in the comparative performance studies. Total detention time through each pair of columns was 26 minutes and the hydraulic loading rate was 3.5 gpm/ft^2.

TERMINOLOGY

Since ozone is only partially soluble in water, a fraction of the ozone applied to wastewater effluent is usually not transferred to the solution and escapes from the contact chamber as off-gas. The ozone that does not escape as off-gas is called the transferred ozone. Ozone which is transferred to the wastewater effluent is either utilized in various chemical reactions (consumed ozone) or remains dissolved in the effluent (residual ozone). The amount of ozone actually consumed by the wastewater effluent is therefore determined by subtracting the amount of off-gas ozone and the amount of residual ozone from the amount of applied ozone.

The concentration of ozone present in an aqueous solution is expressed as milligrams of ozone per liter of fluid (mg/l). Ozone production is commonly expressed in pounds per day (lb/day) and gas concentration as mg/l or percent by weight (% by wt). The latter refers to the fraction of ozone in an air or oxygen stream.

TEST PROCEDURES AND SAMPLING METHODS

All tests were performed in accordance with Standard Methods whenever possible. The bacterial density was estimated by the 5-tube, 3-dilution technique as outlined in Standard Methods (13th Edition). Enumeration of the virus was performed by the plaque technique using African Green Monkey kidney cells. In the natural virus experiments, the virus was identified by a 4-cell line screening technique. A detailed description of the virus concentration and enumeration techniques is presented in Appendix A.

The applied, unused, and residual ozone were measured by the standard iodometric method. A description of the procedure and calculation is shown in Appendix C.

In the initial phase of the study with Ozonation System No. 1, only grab samples were collected. This is because the system was operated for only a few hours daily. For the studies with Ozonation Systems No. 2 and 3, both grab and composite samples were collected. These systems were operated continuously five days per week. The grab samples were collected for bacteriological and water quality analyses. The composite samples were collected for water quality analyses to indicate the performance of the system. These samples were kept in a refrigerator at 15°C and the sampler was set for collection at hourly intervals over a 20-hour period.

The samples for water quality analyses were collected in glass or polyethylene bottles. Bacteriological samples were collected in specially prepared sterilized glass bottles containing traces of $Na_2S_2O_2$ solution. The chemical was added to remove any residual ozone which may remain in the sample. Virus samples were collected by subjecting the sample stream to three stages of concentration: membrane adsorption, chemical flocculation, and alginate filtration.

SECTION 5

RESULTS AND DISCUSSION

PHASE 1

Evaluation of Ozonation Systems

Ozonation System No. 1 (Figure 2) was constructed to allow an evaluation of two ozone contacting methods, the sparger and the positive pressure injector (PPI). The key to an economic usage of ozone depends largely on efficient contact of ozone and bacteria in wastewater. There was no general agreement among the ozone manufacturers as to the most cost-effective method of dissolving ozone in wastewater effluent. The selection of a contactor which would most effectively dissolve ozone is of great importance because of the high cost of producing ozone. A reduction in ozone consumption would reduce the cost considerably and hence make the process more competitive with chlorine.

Figure 7 shows the results obtained with the sparger and injector in secondary effluent. Note that these devices were evaluated in a single-stage contactor.

For the sparger, the ozone transfer efficiency decreased rapidly with increasing ozone dose. At an applied ozone dosage of 10 mg/l, the transfer efficiency was about 70 percent.

For the injector, the ozone transfer efficiency was greater than the sparger at all of the applied ozone dosages. As much as 90 percent of the applied ozone was transferred at an ozone dosage of 10 mg/l. The remaining 10 percent of the ozone was given off as unreacted gas.

An effort was made to improve the ozone transfer efficiency by increasing the time of contact between ozone and the wastewater effluent. Accordingly, Ozonation System No. 2 was designed to operate with a multi-stage contactor system. This arrangement was not incorporated into System No. 1 because of insufficient ozonator capacity.

The performance of Ozonation System No. 2 is also summarized in Figure 7. Improved ozone transfer was found for this system over the entire range of ozone dosages investigated. Transfer efficiencies of 90 percent or greater were obtained at all dosages for this system. It is presumed that the improved ozone transfer efficiency detected in System No. 2 is the result of the multiple stage operation.

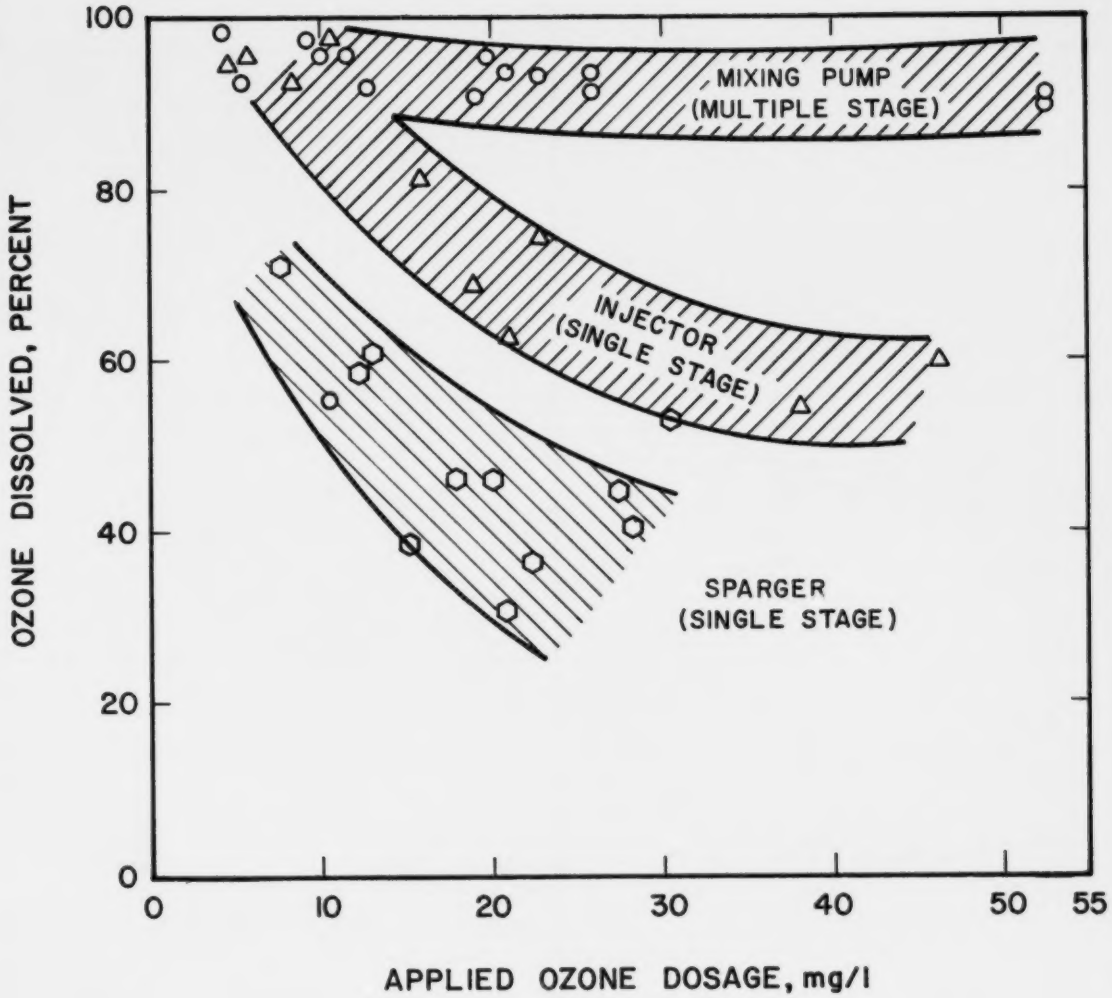


Figure 7 Performance of Ozone contacting systems.

Referring to Figure 8, all contactors were able to remove the first 2 logs (99 percent) of total coliform from secondary effluent with 10 mg/l or less ozone dosage. This removal is adequate to meet effluent standards in some regions of the country. In California, removal of 4 to 6 logs of total coliform is necessary since the requirement calls for a total coliform of 2.2 or less MPN per 100 ml in the disinfected effluent. To accomplish this removal requires an ozone dosage in excess of 50 mg/l for all three contacting systems or 5 times the dosage required to accomplish an additional 2 logs coliform removal. A high dosage was necessary because of the demand from organic content in wastewater. Because of this, ozone's attractiveness as a disinfectant diminishes. One other alternative was to pretreat the effluent prior to ozonation.

Evaluation of Various Process Effluents

Pretreatment studies were conducted using effluents from several pilot plant processes. These systems were operating concurrently with the ozonation system. The availabiity of these effluents enabled the evaluation of pretreatment systems which would be most compatible for ozone disinfection application. The quality of these effluents varied throughout the experimental period. Consequently, the effluent character reported in the study may not be typical of the process studied.

The study was conducted using Ozonation System No. 2. This system was used because it demonstrated excellent ozone transfer efficiency in the initial stage of the study. Economically, it was not known how the mixing pump device would compare with the sparger on a large scale installation. Concern at that time was directed toward determining the least ozone dose required to achieve the disinfection goal of the pilot plant study.

In reviewing the results, it was found that pretreating the effluent had significantly reduced the ozone dose requirement for disinfection in some cases. Effluents with low soluble COD, nitrite, and suspended solids generally reacted very favorably to ozone during disinfection. A reduction of as much as 90 percent of the ozone dose requirement was found in the pretreated effluents.

An attempt was made to determine the effects of the NO_2-N, suspended solids and soluble COD on ozone disinfection. A comparison of the water quality parameters of effluents shown in Table 2 indicates several similarities among the effluents.

Referring to the table, note that two of the three parameters in each case were similar. For example, the non-nitrified secondary and carbon-treated effluents had soluble COD within 5 mg/l difference and suspended solids of less than 10 mg/l. The nitrified and filtered, non-nitrified secondary had similar concentrations of soluble COD and NO_2-N. The physical-chemical treatment and filtered, nitrified secondary, however, had low NO_2-N of less than 1 mg/l and suspended solids of less than 13 mg/l. In each case, the difference in the third parameter for both effluents was substantial as shown in the underlined numbers in Table 2. Because of the above similarities, it was felt that a comparison of the disinfection performance from the effects of the third parameter can be made. Figures 9, 10, and 11 show the respective effects of NO_2-N, suspended solids, and soluble COD on ozone disinfection.

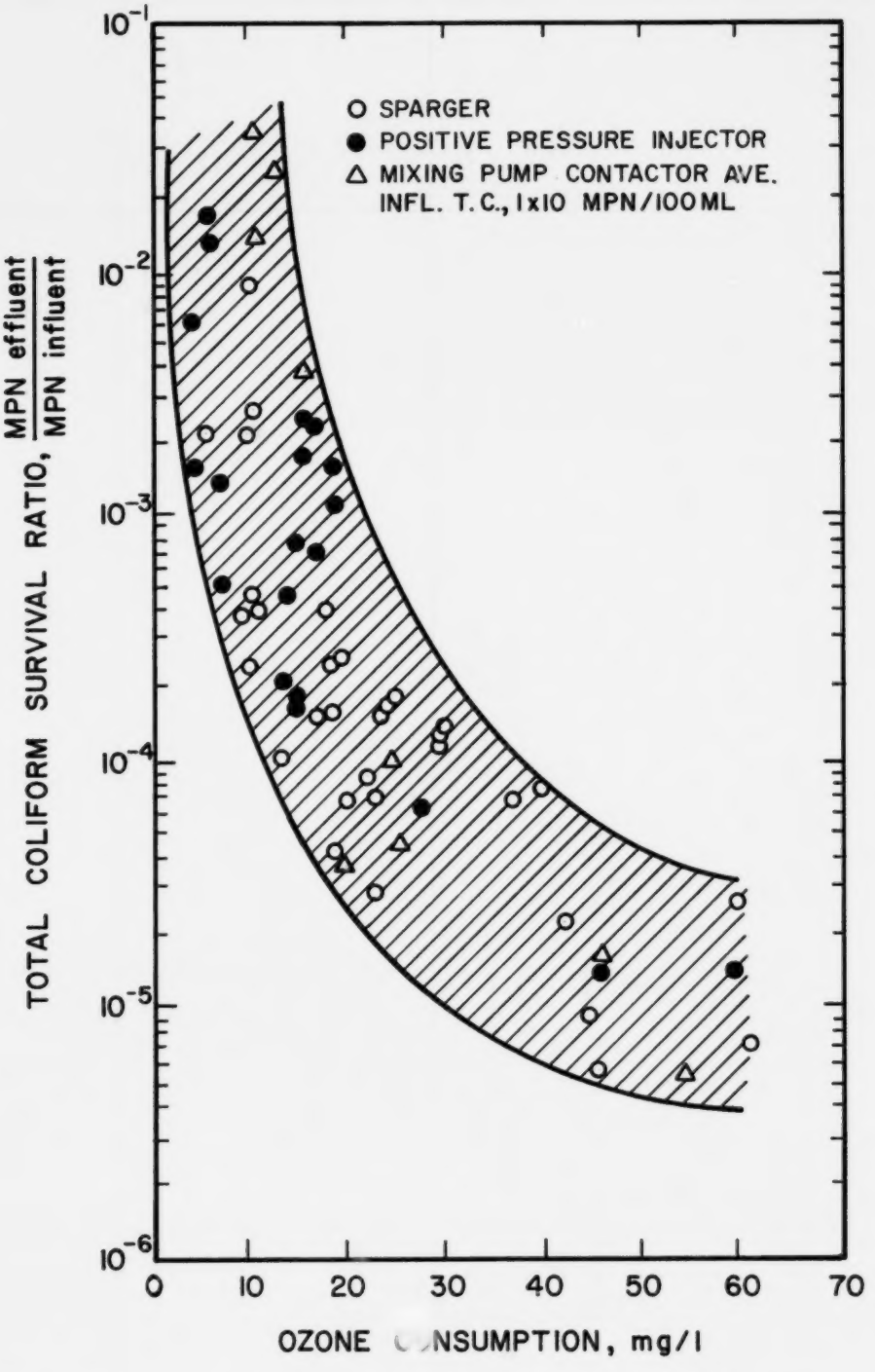


Figure 8 Disinfection results of ozonation system No. 1 and No. 2.

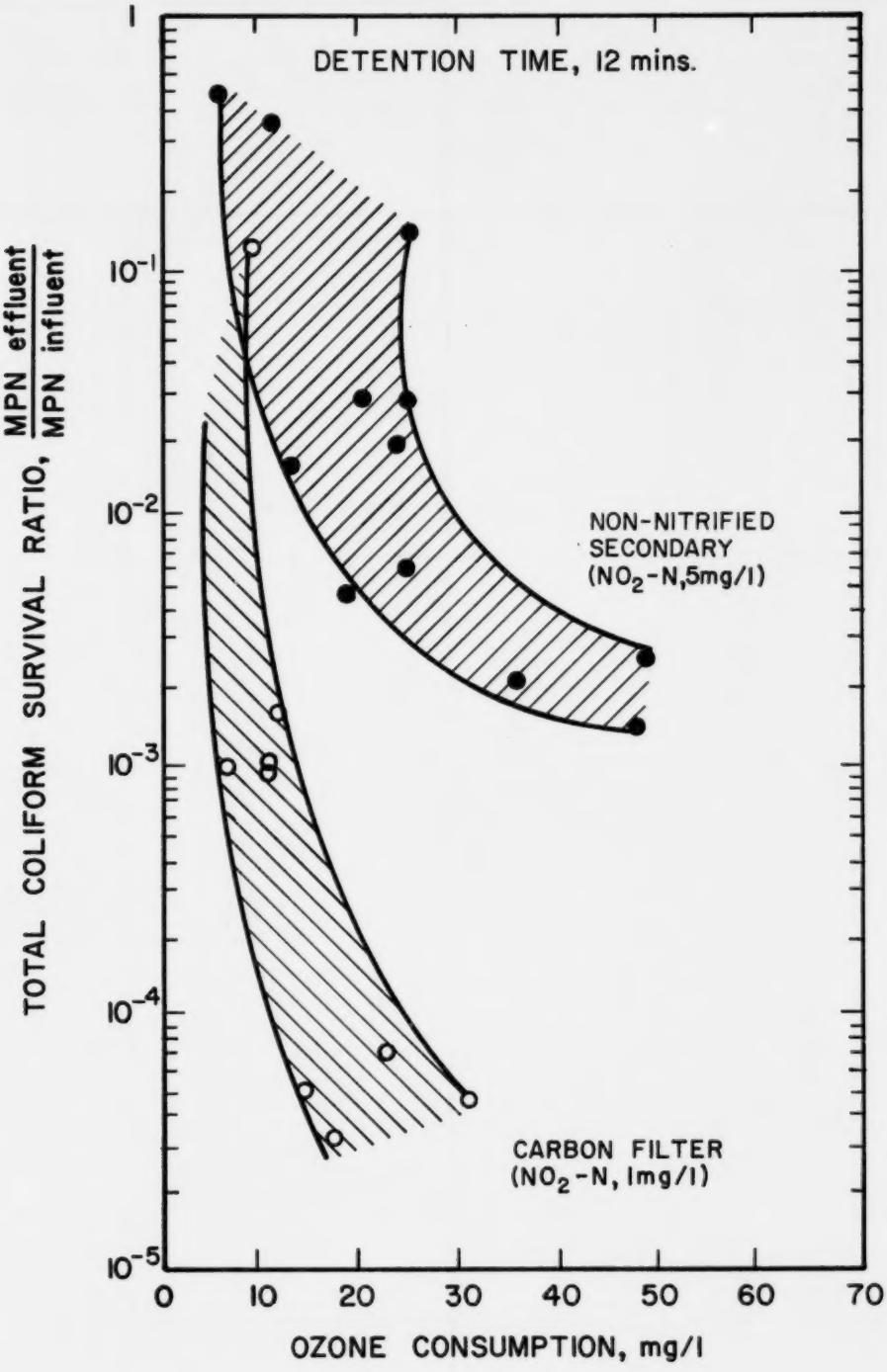


Figure 9 Comparison of disinfection performance-Case I.

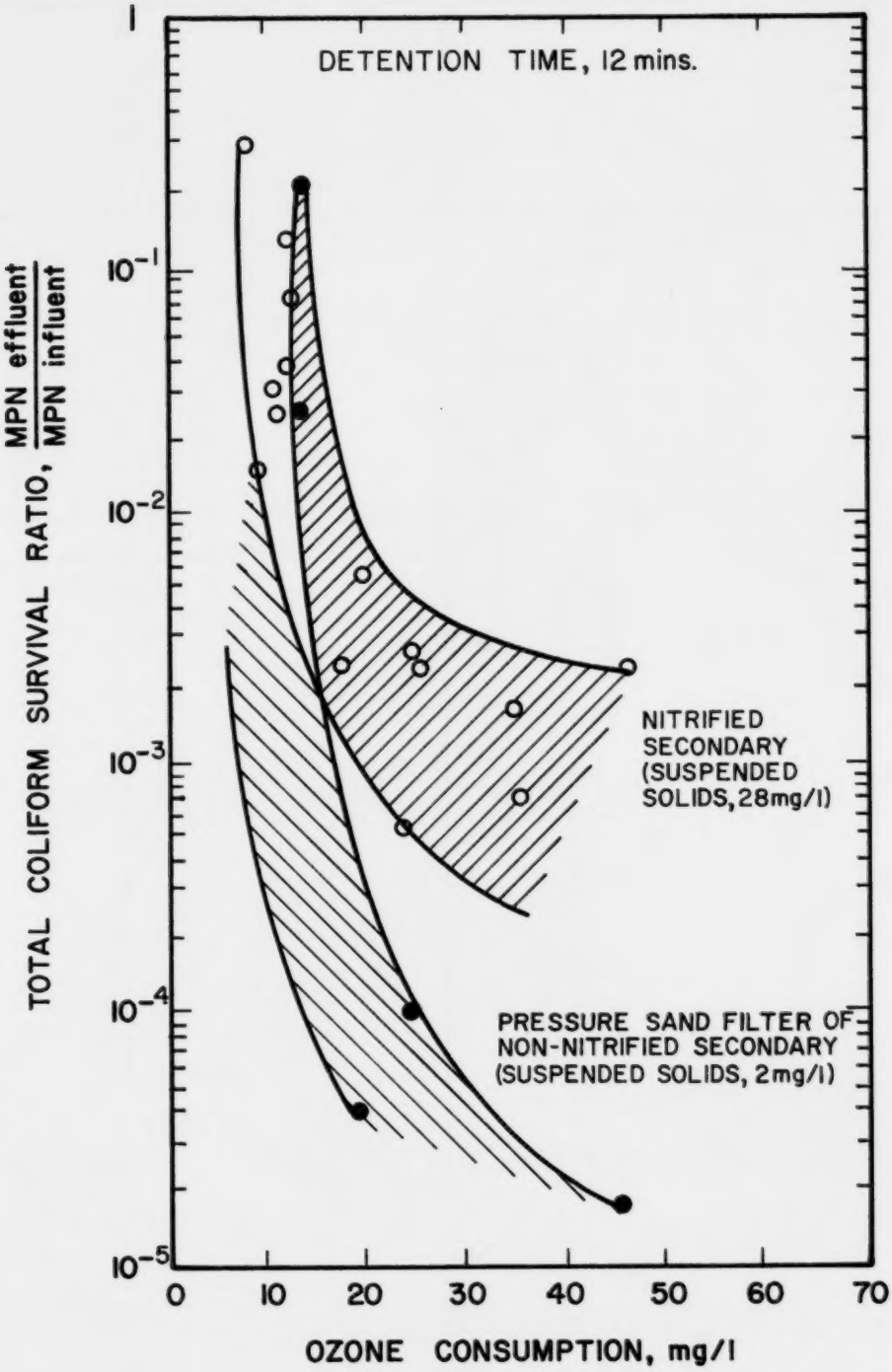


Figure 10 Comparison of disinfection performance-Case II.

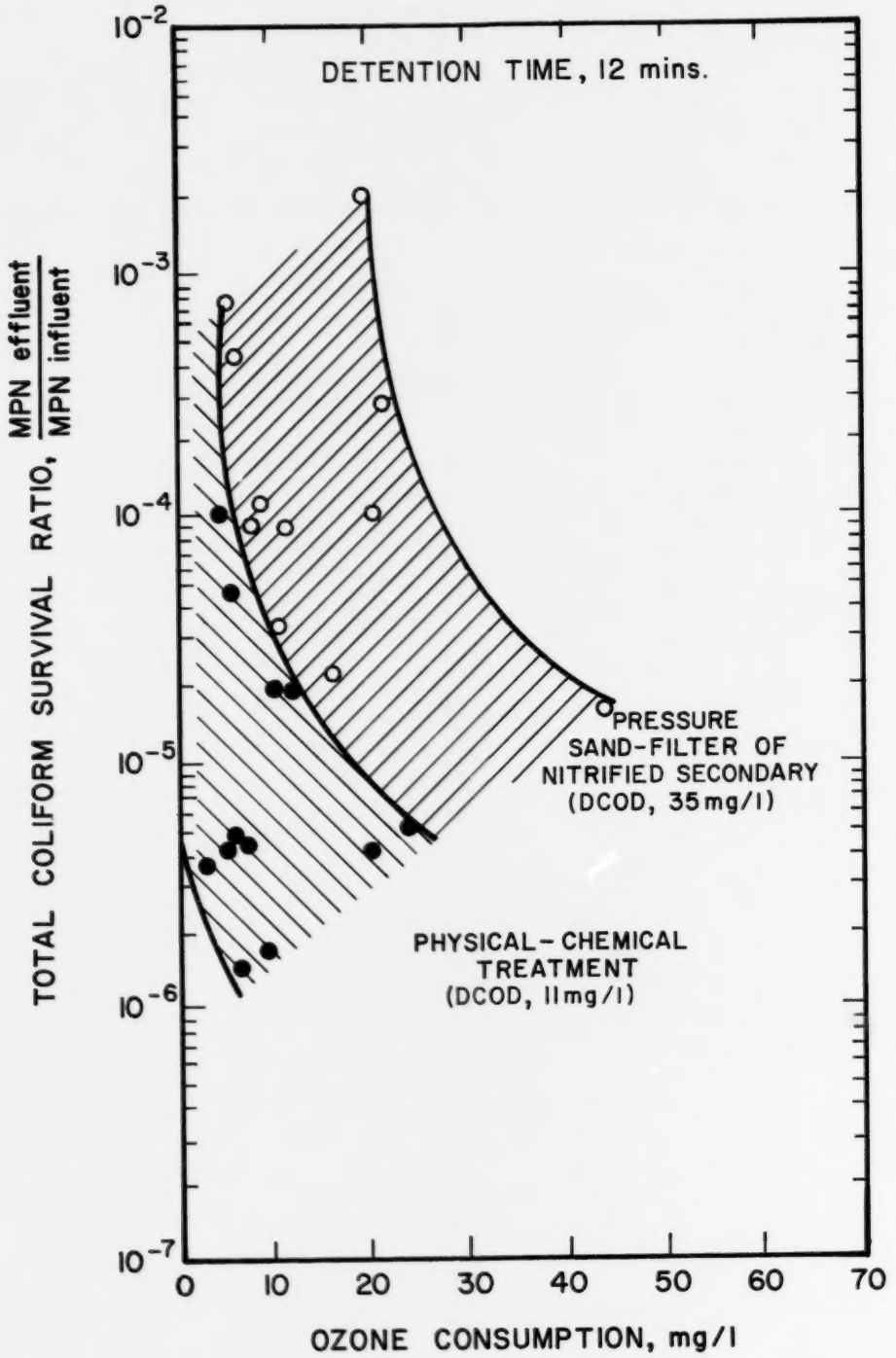


Figure 11 Comparison of disinfection performance-Case III.

Referring to Figure 9, note the influence the NO_2-N had on disinfection with ozone. The high NO_2-N concentration of 5 mg/l seems to have reduced ozone's effectiveness as a disinfectant by limiting its total coliform reduction to 3 logs or less. Similar disinfection response was also found for effluents with a high concentration of suspended solids. Figure 10 shows a total coliform reduction of about 3 logs for the nitrified effluent which had high suspended solids concentration of 28 mg/l. By comparison, the filtered, non-nitrified effluent with suspended solids of 2 mg/l had a total coliform reduction of 5 logs.

Figure 11 shows the effects of soluble COD on filtered, nitrified effluent which had a high soluble COD concentration of 35 mg/l. The total coliform reduction in this effluent was 1 to 2 logs less than the physical-chemical treatment effluent. The soluble COD concentration in the physical-chemical treatment effluent was 11 mg/l.

In Case 1 (Figure 9) the total coliform count in both non-ozonated effluents was almost equal. In Cases 2 and 3 (Figures 10 and 11), the total coliform difference in the experimental waters was about 1 to 2 logs. The effects from total coliform variation in the range found for the Pomona effluents were probably insignificant. For example, in Figure 11, the physical-chemical treatment effluent had greater coliform reduction than the filtered, nitrified secondary even though its influent total coliform level was greater.

Evaluation of Compounds Removed by Ozone

In addition to effluent disinfection, the effect of ozonation was examined in terms of the treatment of several water quality parameters. Ozone has a very high oxidation potential of -2.07 volts. It is very unstable and will oxidize most carbonaceous and nitrogenous materials present in wastewater.

The removal of color through oxidation of color-forming substances was examined. Figure 12 shows color removal curves developed for effluents of the various unit processes. The PCT effluent exhibited sufficiently low color prior to ozonation and, therefore, was not studied.

All effluents displayed a reduction in color subsequent to ozonation. The color removal pattern may be divided into two stages -- the primary stage where oxidation of most of the color-forming substances occurred and the secondary stage where removal of the refractory compounds occurred. The amount of ozone consumed per unit of color removed was considerably higher in the secondary stage than in the primary stage. The transition zone between first and second stage removal appears to occur in the region between 40 and 60 percent removal of color. Ozone consumption per unit of color removal was considerably less prior to the transitional zone. This zone may be significant in the cost studies pertaining to the removal in wastewater effluents.

Figure 13 shows the effect of detention time on color removal with ozone. Most of the color removal occurred in the initial two minutes with very little removal occurring after two minutes. Rapid reaction was found in all the effluents studied.

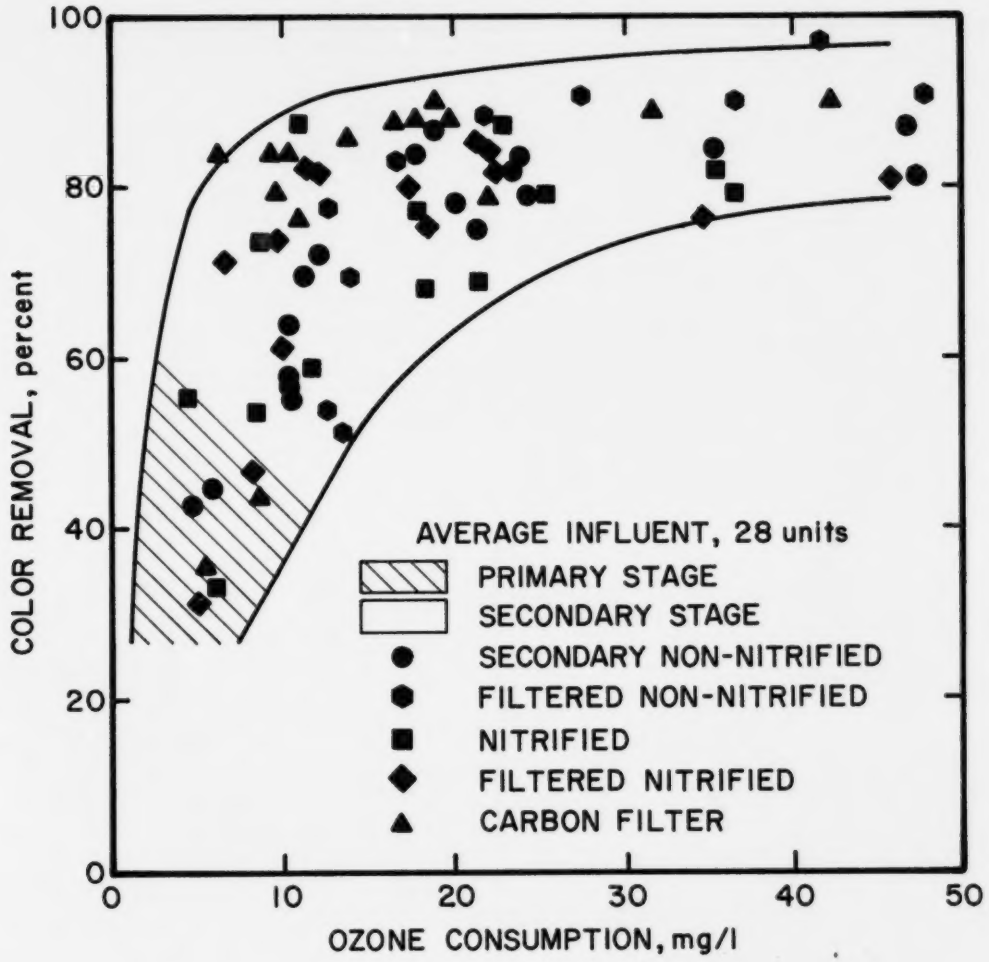


Figure 12 Color removal with ozone.

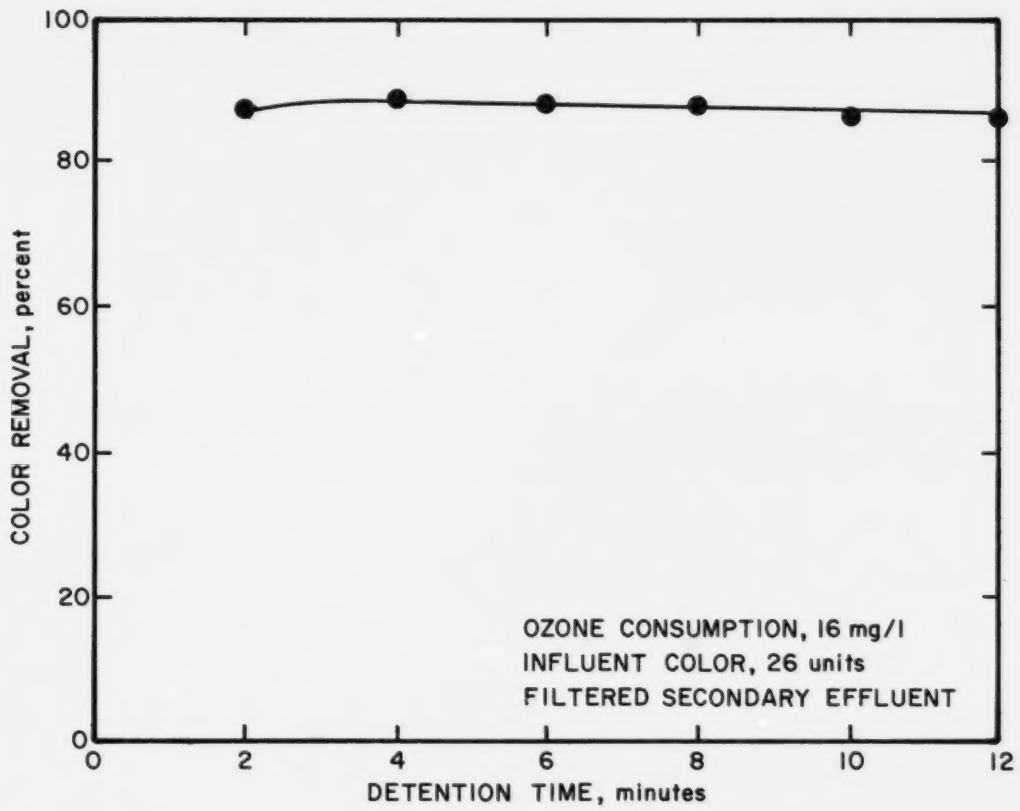


Figure 13 Effects of contact time on color removal with ozone.

Ozonation was also associated with reductions in suspended solids, turbidity, total COD, and soluble COD. In addition, nitrite was oxidized to nitrate while ammonia-N remained relatively unchanged.

Results of suspended solids and turbidity removal through ozonation of the various process effluents are presented in Table 3. The filtered secondary, carbon filter and physical-chemical treatment effluents were not presented because of the low levels of suspended solids found. The concentration of suspended solids and level of turbidity detected in ozonated effluents fluctuated with the ozone contact period. An increase in the initial effluent values was detected on several occasions. The highest percentage suspended solids and turbidity removal occurred in the nitrified effluent.

The removal of suspended solids is attributed to oxidation and flotation mechanisms. The formation of froth has been described as due to the oxidation of certain elements in wastewater measured as suspended solids and total COD. Effluent with high suspended solids are suspected of containing high concentrations of froth generating elements. The net result is a production of more froth and, hence, more entrapment of the suspended material. In the Pomona studies, the nitrified effluent had high levels of suspended solids. This may have led to substantial froth generating during ozonation and, hence, substantial removal of suspended solids.

Ozone readily reacts with organic substances. The COD associated with suspended solids can either be oxidized or trapped in the froth generated during ozonation. Table 4 shows total COD removal for all effluents investigated. The most consistent results with respect to total COD removal occurred in non-nitrified effluent. The nitrified effluent was least consistent and had a total COD increase after ozonation in some of the experiments. Referring to Table 1, this effluent also had high suspended solids and turbidity prior to ozone treatment. It is possible that the transformation of suspended solids and turbidity into soluble by-products by ozone added to the concentration of soluble COD detected and, therefore, minimized the reduction of soluble and total COD.

The pH of the ozonated effluent remained relatively unchanged after ozonation. Table 5 shows a summary of the pH values for the various process effluents before and after ozonation. High alkalinity of the effluents in the study may explain why pH was not affected by ozonation.

Ammonia-N oxidation by ozone at high pH have been reported by others. The NH_3-N in the pilot studies did not seem to be affected by ozone at normal pH found in the Pomona effluent. The NO_2-N in all the effluents was easily oxidized to the NO_3-N. Tables 6, 7, and 8 show the effects of ozone oxidation on the nitrogenous compounds in wastewater.

PILOT PLANT PHASE

Selection of Contacting System

Several considerations were given in the selection of a contacting system for the pilot plant studies. In phase 1, it was found that the disinfection performances of the sparger and injector were similar. Moreover, ozone transfer

TABLE 3. OZONATION EFFECTS ON SUSPENDED SOLIDS AND TURBIDITY

Parameter	Ozone Consumption mg/l	Non-Nitrified Secondary	Nitrified	Pressure-Filtered Nitrified
Suspended Solids Removal, percent	5	*(22)	8	5
	10	(23)	-	(10)
	15	24	39	10
	20	18	45	(6)
	25	25	38	4
	35	50	-	-
	40	-	43	9
	50	52	64	1
Turbidity Removal, percent	5	(2)	(3)	24
	10	4	(3)	24
	15	2	23	57
	20	31	36	58
	25	20	42	60
	40	55	71	84
	50	55	73	71

* ( ) Increase

TABLE 4. OZONATION EFFECTS ON TOTAL AND SOLUBLE COD

Parameter	Ozone Consumption, mg/l	Non-Nitrified Secondary	Filtered Secondary	Nitrified Secondary	Filtered Nitrified	Carbon Treated	P-C-T
Total COD Removal, Percent	5	8	-	2	14	-	-
	10	10	-	* (3)	7	18	10
	15	(1)	-	12	29	14	17
	20	13	8	7	37	32	2
	25	9	35	-	56	26	13
	30	-	-	9	-	-	13
	35	-	37	-	-	-	-
	40	19	38	20	67	15	7
	50	13	25	30	53	26	3
Soluble COD Removal, Percent	5	6	-	(20)	3	3	7
	10	4	-	10	3	17	(1)
	15	2	5	(20)	13	15	4
	20	7	14	(47)	10	44	(2)
	25	1	37	20	14	26	(8)
	35	-	35	-	-	-	-
	40	20	-	3	17	(12)	2
	50	18	24	6	20	15	27

* ( ) Increase

TABLE 5. OZONATION EFFECTS ON pH

Ozone Consumption mg/l	Non-Nitrified Secondary	Filtered Secondary	Nitrified	Filtered Nitrified	Carbon	P-C-T
5	*7.3/7.5	--	7.2/7.2	7.3/7.4	--	6.9/7.1
10	7.3/7.5	--	7.0/7.3	7.2/7.4	7.5/7.6	6.9/7.1
15	7.3/7.5	7.2/7.4	7.2/7.2	7.1/7.2	7.5/7.7	7.0/7.1
20	7.3/7.5	7.3/7.5	7.0/7.1	7.2/7.3	7.4/7.6	6.9/7.0
25	7.3/7.4	7.4/7.5	7.1/7.2	7.0/7.3	7.5/7.6	7.0/7.1
10	--	--	--	7.0/7.1	--	7.2/7.3
35	--	7.1/7.3	--	--	--	--
40	7.3/7.4	7.6/7.6	7.1/7.2	7.0/7.1	7.5/7.5	6.7/7.0
50	7.2/7.3	7.3/7.3	7.0/7.1	7.3/7.3	7.4/7.6	7.2/7.2

* Before/After Ozonation

TABLE 6. OZONATION EFFECTS ON AMMONIA-N (mg/l)

Ozone Consumption mg/l	Non-Nitrified Secondary	Filtered Secondary	Nitrified	Filtered Nitrified	Carbon	PCT
5	*13/13	--	2/2	4/4	--	25/25
10	14/13	10/10	2/3	3/3	12/11	22/22
15	14/14	9/9	2/2	4/4	10/10	20/20
20	15/15	10/10	2/3	2/2	10/10	18/18
25	13/13	10/10	2/3	-	-	17/17
30	-	-	-	-	11/11	-
35	12/12	-	-	4/4	-	-
40	-	10/10	3/4	1/1	8/8	16/16
50	13/13	11/11	2/3	1/1	-	-

* Before/After Ozone

TABLE 7. OZONATION EFFECTS ON NITRITE-N (mg/l)

Ozone Consumption mg/l	Non-Nitrified Secondary	Filtered Secondary	Nitrified	Filtered Nitrified	Carbon	PCT
5	*5/3	--	1.3/0.5	1/0.2	--	0.1/0.05
10	6/2	3/0.5	1.1/0.2	1/0	1/0.3	0.1/0.05
15	5/0	3/0.1	1.4/0.2	-	0.8/0.1	0.1/0.05
20	5/0	3/0	1.3/0.1	0.3/0	1.3/0.2	0.1/0.05
25	6/0	3/0	1.0/0.1	-	3/0.3	0.1/0.05
30	-	-	-	-	0.6/0.1	-
35	4/0	-	0.7/0.1	1.2/0	-	-
40	-	4/0	-	0.4/0	2.8/0.2	0.1/0.05
50	5/0	2/0	0.6/0.1	0.4/0	-	-

* Before/After Ozonation

TABLE 8. OZONATION EFFECTS ON NITRATE-N (mg/l)

Ozone Consumption, mg/l	Non-Nitrified Secondary	Filtered Secondary	Nitrified	Filtered Nitrified	Carbon	PCT
5	*0/2	-	4/5	5.9/6.2	-	4/5
10	0/3	0.2/3	5/6	8/9	0.3/1/7	5/5
15	0/5	0.3/3	8/9	9/11	0.1/1.2	5/5
20	0/4	0.1/4	7/8	6/7	0/2	4/4
25	0/4	0.2/4	6/6	12/12	-	5/5
30	0/4	-	-	-	0.1/0.9	-
35	-	-	5/5.5	-	-	-
40	-	0.2/2.4	-	6/7	0/3	4/4
50	0/4	-	7/7.6	11/12	-	-

* Before/After Ozonation

was improved by a multiple-stage contacting system. For the pilot plant studies, the sparger was selected because it is inexpensive and requires less energy than the injector. It is also a proven device, having been in use for injecting ozone into potable water for many years. The sparger was incorporated into a multiple-stage contacting system to improve transfer efficiency. Figure 14 shows ozone transfer efficiency of the sparger in single-stage and in multiple (six) stage contactors.

Ozone Generator--

The PCI generator was used in the pilot plant studies. The main features of the generator were the cooling system and dielectric tube design. Both silicone oil and water were used to cool the generator. Two large dielectric tubes were used in place of the more conventional tube arrangement which consists of as many as 50 small dielectric tubes. The use of high frequency purportedly permits the use of fewer dielectric tubes.

Air Preparation and Oxygen Equipment--

The air preparation equipment is necessary for optimum ozone production. Moist air will cause corrosion and traps dirt and particles in the equipment. These will ultimately cause a malfunction in the equipment. Dessicants were selected to provide air with dew point of -40°F. An oil-free air is critical for best ozone production in the dielectric. Oxygen was taken from a liquid oxygen storage tank.

Operational Experiences

Water Quality--

Sufficient ozonation of wastewater effluent generally produced an effluent with virtually no color, and low levels of suspended solids and bacteria. In addition, reduced levels of many effluent impurities were noted.

Ozonator--

The ozonators operated continuously for a year with no major breakdown. Slight modifications were made in order to improve the performance and reliability considerably. Most of the service on the ozonators was performed by the ozone manufacturer.

The generator experienced some problems initially due to power surges (spikes) from the electrical lines. The surges were thought to originate from short-circuiting of a micro-switch which controlled a large hopper-actuated valve in the research facility. Heat was generated in an electrical line whenever a surge occurred. It was the heat generated by the impulse which consequently burned the diodes, silicone control rectifiers, contactor and D.C. breaker switch in the ozonator. These components convert the 60 cycle AC power supply in the generator to the DC power supply before converting it back to AC again at a high frequency of 2000 cycles. Varistors were installed to clip the power spikes in the line.

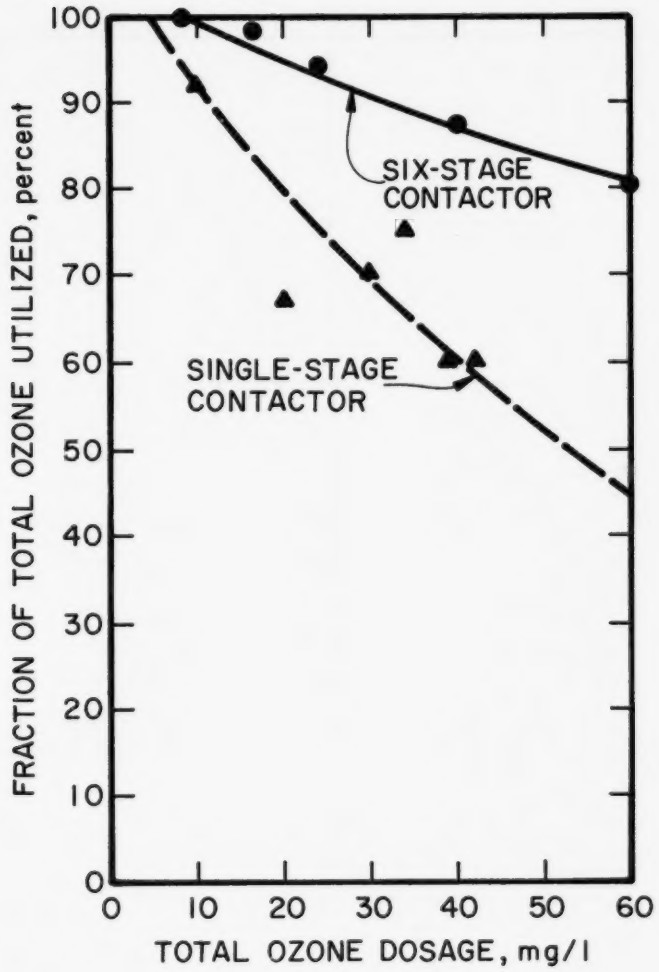


Figure 14 Performance of single and multiple stage contacting system.

Another problem occurred when a leak in the cooling system caused silicone oil, which removed heat from the ozone generative cell, to leak into the ozone/air line leading to and from the ozonator. The leak was the result of improper placement of cell gaskets during the assembly and a pinhole crack in the heat exchanger.

Breakage of the dielectrics was also noted. This was the result of mishandling of the equipment during shipment to the Pomona site and overtightening of the cell during the assembly.

Contacting System--

The six-stage contacting system performed well during the pilot studies. The flexibility of the system allowed dosage controls to meet demands from the effluent in each chamber. Success of the system operation was evidenced by the small percentage of ozone off-gas detected from the contact columns.

The diffusers clogged after nine months of operation. An examination showed many pits in the diffusers and discoloration of the stainless steel material.

Air Preparation Unit--

Figure 15 shows the operating sequence for the air dryer which controlled the dew point at or below -40°F.

Startup difficulties encountered with the dryers were related to separating water from air and cooling the discharged air. Excessive water was found in the dessicants and the desired dew point was not obtained. Modifications were made to the system by adding water traps and an after-cooler. Figure 16 shows the revisions made to the system. A check of the dew point with an Alnor meter showed the dew point to be at or below -40°F in the discharged air.

Ozone Analyzer--

Two ozone analyzers were evaluated in the study, namely, the Source Gas Analyzer (SGA) and the Dasibi Analyzer (Model 1003). These analyzers measure ozone in the gas phase.

The disadvantages of the SGA unit were the need for frequent calibrations and the use of nitric oxide as a reference gas. The calibrations were made after the ozone concentration was changed.

The Dasibi unit maintained its accuracy following changes in ozone concentration. However, the analyzer required a cell cleaning once per week to maintain its precision.

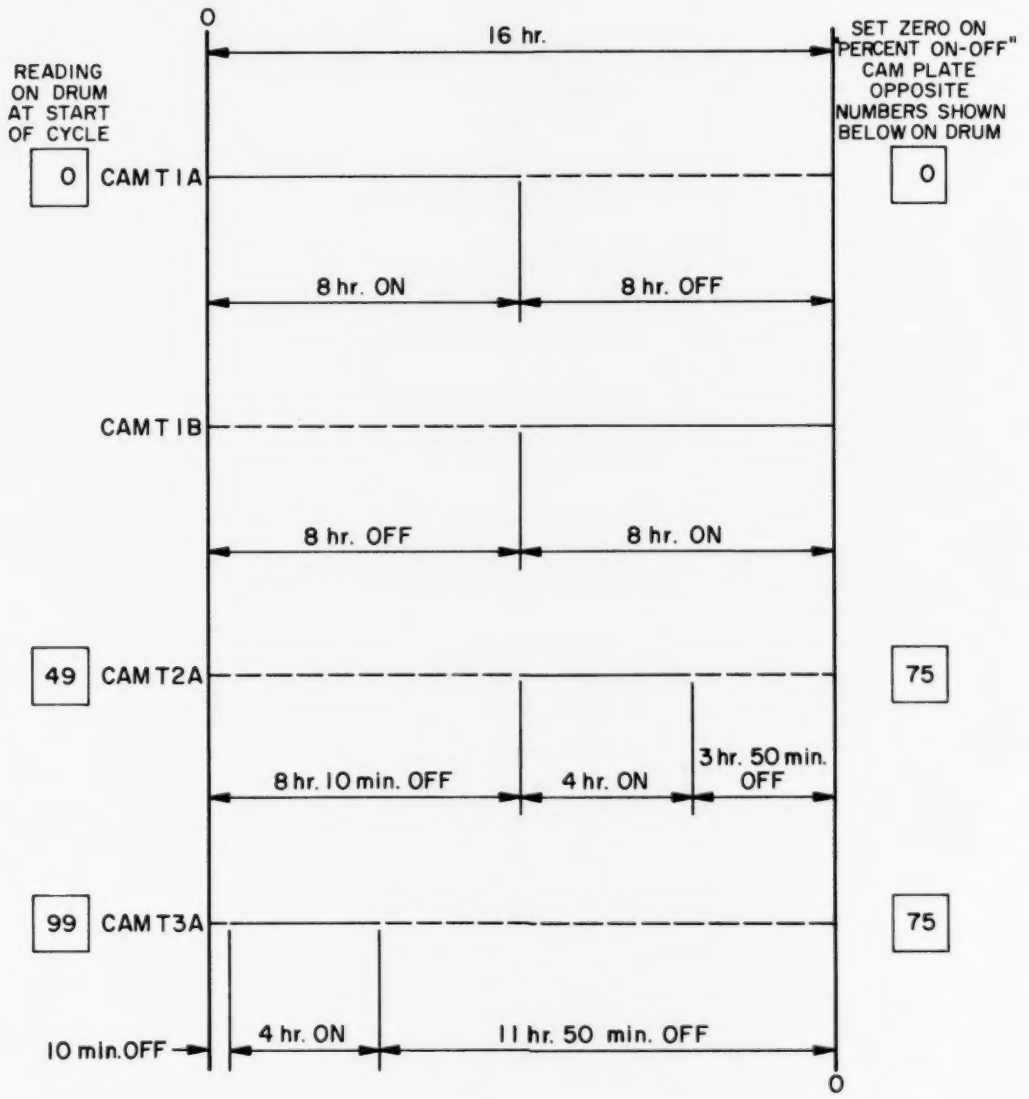


Figure 15 Air dryer 8 hour tower reversal cycle 4 hour reactivation heating period.

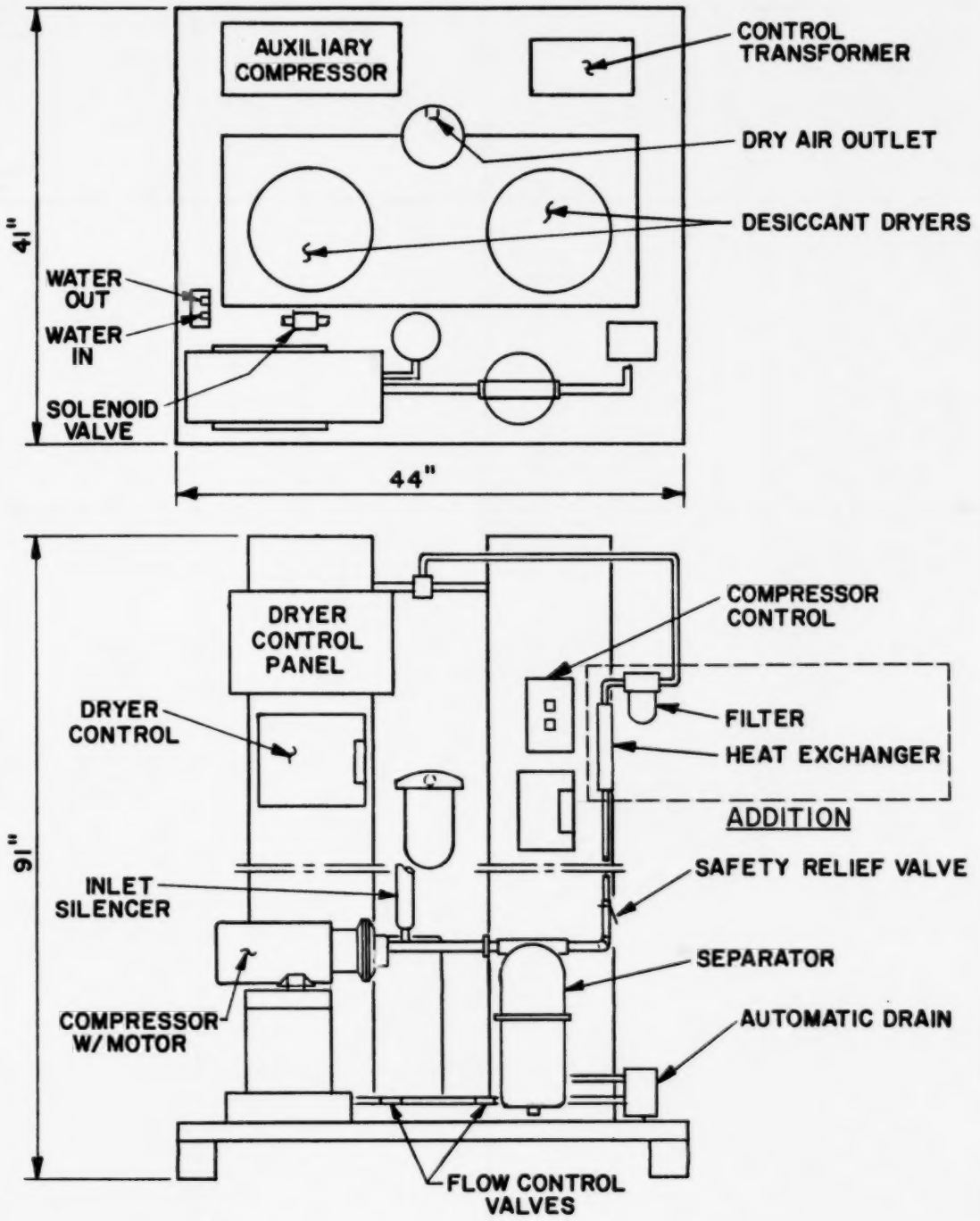


Figure 16 Addition to air drying unit.

Pilot Plant Results

Bacterial Removal--

Two coliform bacteria standards were evaluated in the pilot plant studies, namely, the California standard and the original EPA standard. The EPA standard has been withdrawn by the Agency. The California standard specifies a seven-day median total coliform of less than 2.2 MPN per 100 ml. The EPA standard specified a maximum fecal coliform count of 200 MPN per 100 ml.

Studies were performed with secondary effluent and carbon filter effluent to verify phase 1 results. With secondary effluent, the ozone dosage ranged from 10 to 60 mg/l. Eighteen trials were performed for each ozone dosage. For the carbon effluent, the ozone dosage ranged from 1 to 6 mg/l. Substantially less ozone was added to the carbon filter effluent because of lower demand in the effluent. A total of 13 trials were performed per ozone dosage for this effluent.

Figures 17 and 18 show the percent of the trials which resulted in disinfection sufficent to meet the California and EPA effluent coliform standards, respectively. As was found in phase 1, the ozone dosages required for meeting both disinfection standards were reduced substantially when the effluent was pretreated with activated carbon. In Figure 17, the ozone dosage for meeting the California standard in 50 percent of the trials was reduced from 50 mg/l for the secondary effluent to 5 mg/l for the carbon filter effluent. In Figure 18, the ozone dosage for meeting the EPA standard in 50 percent of the trials was reduced from 10 mg/l for the secondary effluent to 1 mg/l for the carbon filter effluent. Referring to Table 9 which summarizes the two effluent qualities, the carbon filter effluent had much lower soluble COD, nitrite, color, and suspended solids than the secondary effluent. These parameters were identified in phase 1 as affecting ozone disinfection in wastewater. Accordingly, it explains the differences in disinfection responses for the two effluents.

There is also a considerable difference in the ozone dose required to meet the California and EPA disinfection standards. Assuming a typical day for the Pomona effluent, where the influent total coliform averaged about 5 to 6 logs, the California disinfection standard normally would require more than 5 times the dose of the EPA standard. This assumes that the EPA standard of 200 fecal coliform MPN per 100 ml is approximately equal to 1000 total coliform MPN per 100 ml. The difference between this total coliform level and the California standard of 2.2 total coliform MPN per 100 ml is about 3 logs. With this in mind, note that the additional ozone was utilized to remove an additional 3 logs. Use of ozone for wastewater disinfection to meet the California standard thus would not appear to be economical unless it were applied to a tertiary effluent.

Significance of Parameters Affecting Disinfection with Ozone--

Parameters identified in phase 1 as affecting ozone disinfection were color, suspended solids, turbidity, total COD and soluble COD. Experiments conducted with Ozonation System No. 3 provided some insight into the

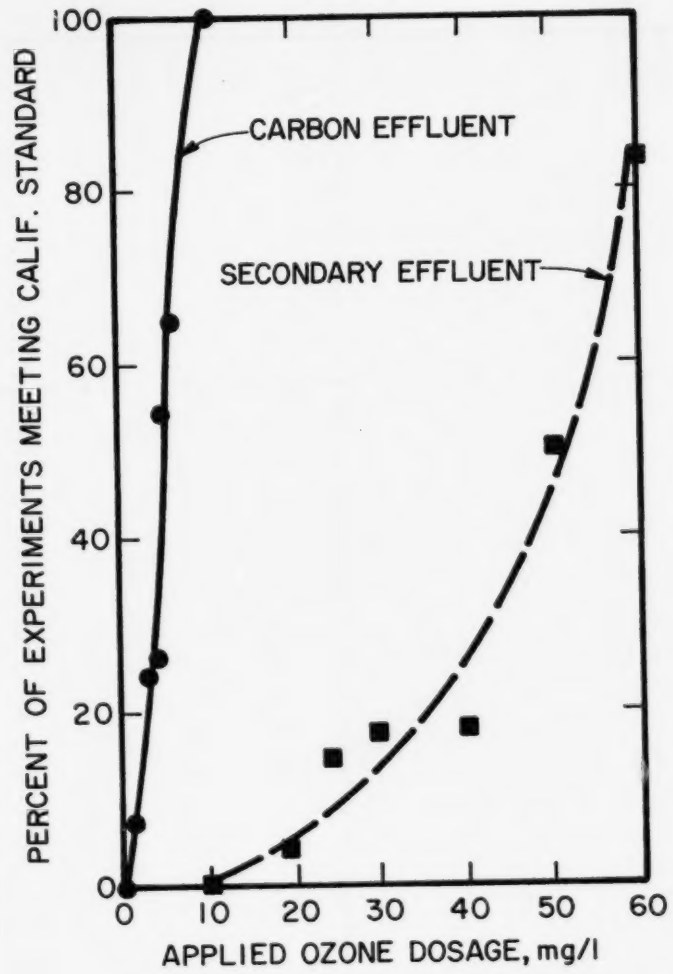


Figure 17 Probability of meeting California disinfection standard with ozone.

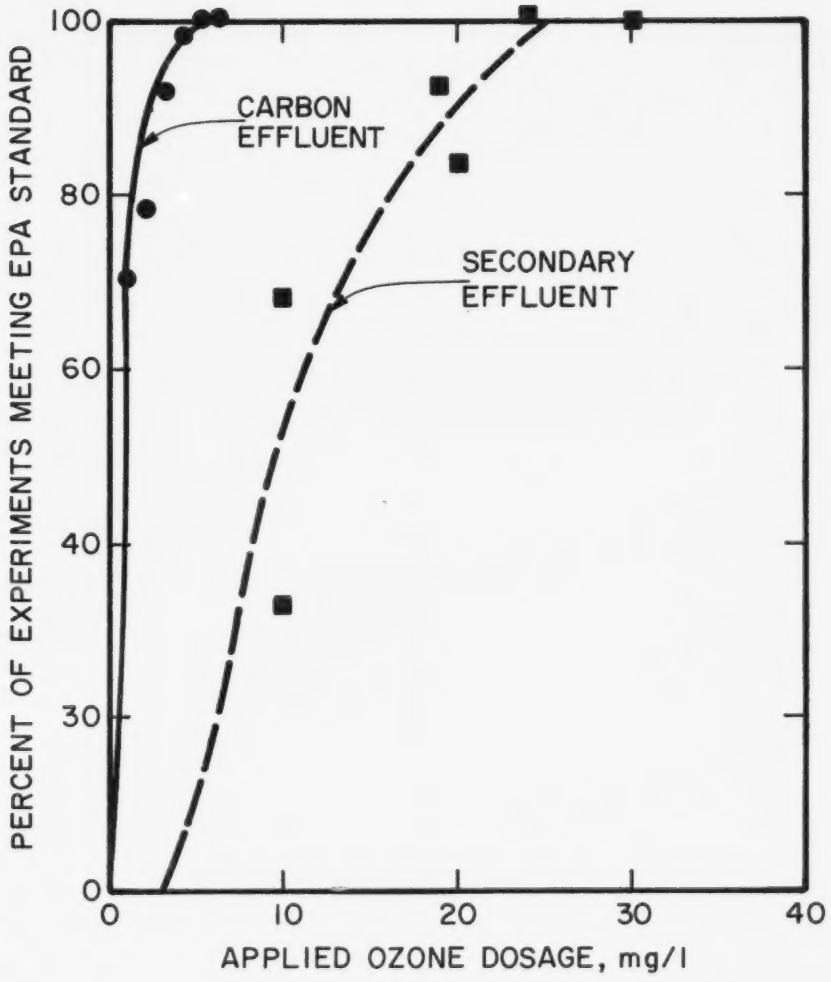


Figure 18 Probability of meeting former EPA disinfection standard with ozone.

TABLE 9. CHARACTERIZATION OF SECONDARY AND CARBON TREATED EFFLUENT

Parameters	Secondary Effluent	Carbon Treated Effluent
Soluble COD, mg/l	20	10
NO_2-N, mg/l	0.5	0.2
Color, units	25	8
Suspended Solids, mg/l	7	2
pH	7.7	7.6
Temp. ^oC	25	25
No. of Experiments	18	13

ozone demanding substances in wastewater which caused the high ozone consumption during disinfection in phase 1.

Figure 19 shows a removal profile through the six contact chambers for the various water quality parameters. The most significantly affected parameters were color and nitrite-N, both of which showed nearly complete removal. The limited suspended solids removal followed a linear relationship in the initial two contact chambers. The lack of further removal indicated that the remaining suspended solids were refractory. Removal of the soluble COD was negligible.

Soluble Chemical Oxygen Demand -- An attempt was made to estimate the ozone consumption by the soluble COD. Figure 20 shows the relationship between the amount of ozone consumed per unit of soluble COD removed and the initial soluble COD concentration in secondary and carbon filter effluents.

An increase of the soluble COD during ozonation occurred occasionally. This was observed first in the pilot plant and then in subsequent laboratory studies. Varying concentrations of ozone solution were prepared by dissolving ozone gas in deionized water. These were mixed with secondary effluent contained in beakers. No detectable suspended solids were found in the mixture after the addition of ozone to the samples in the beakers. There was, however, an increase in soluble COD from the original concentration in secondary effluent.

Insignificant reductions in soluble COD were sometimes observed after ozonation even though high ozone dosages were added to the effluent and residual ozone concentrations in the system were low. It appears that most of the transferred ozone reacted with organic substances in wastewater to form compounds that were still measured as soluble COD.

Figure 21 shows the relationship between total coliform survival ratio and residual soluble COD for an ozone residual of 2 mg/l. An interesting relationship was found between these two parameters (soluble COD residual and total coliform survivors) at a given ozone residual. A high coliform count was found whenever the ozonated effluent exhibited high levels of soluble COD remaining. This relationship was true in samples where the soluble COD was greater than 12 mg/l. When the soluble COD was less than 12 mg/l, the total coliform survivors were independent of the soluble COD remaining. Approximately one log variation in the total coliform survival ratio was found for every 2 mg/l of soluble COD in the effluent.

It should be noted that the relationship established in this study between soluble COD and disinfection may not be applicable to other wastewaters due to the fact that soluble COD measures a wide variety of organic substances in wastewater. The reaction between soluble COD and ozone may vary from one treatment plant to another. Consequently, a similar degree of disinfection may be found for a soluble COD substantially different than the soluble COD in the Pomona effluent.

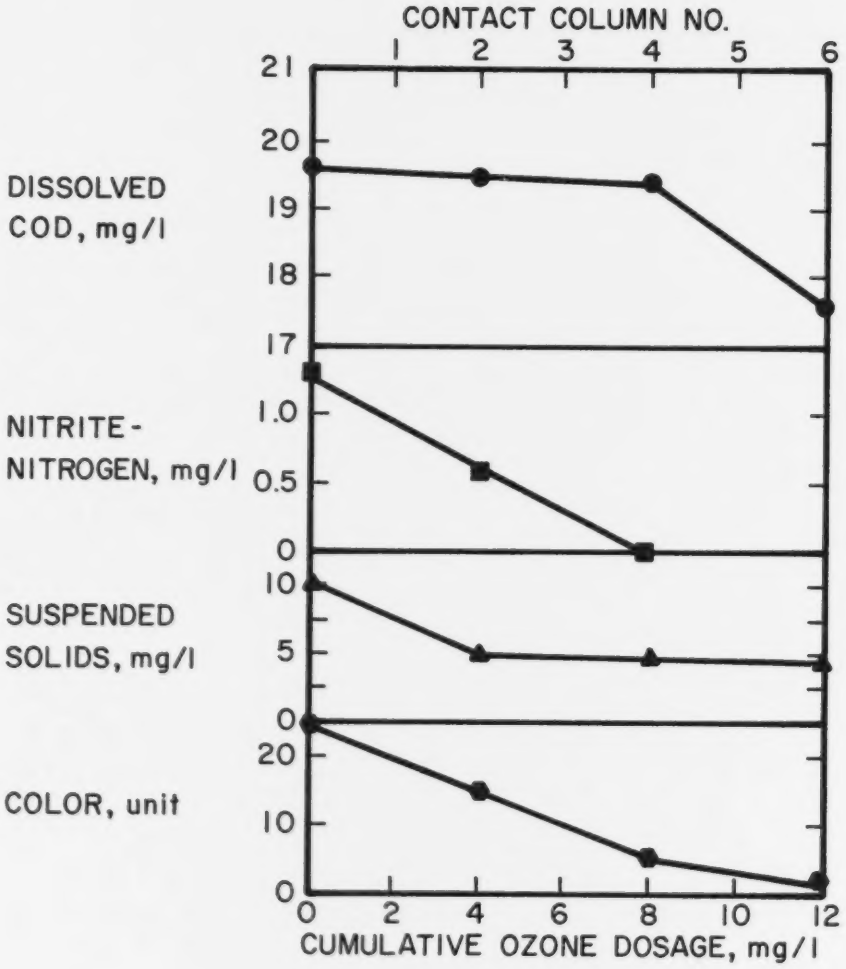


Figure 19 Ozonation of secondary effluent.

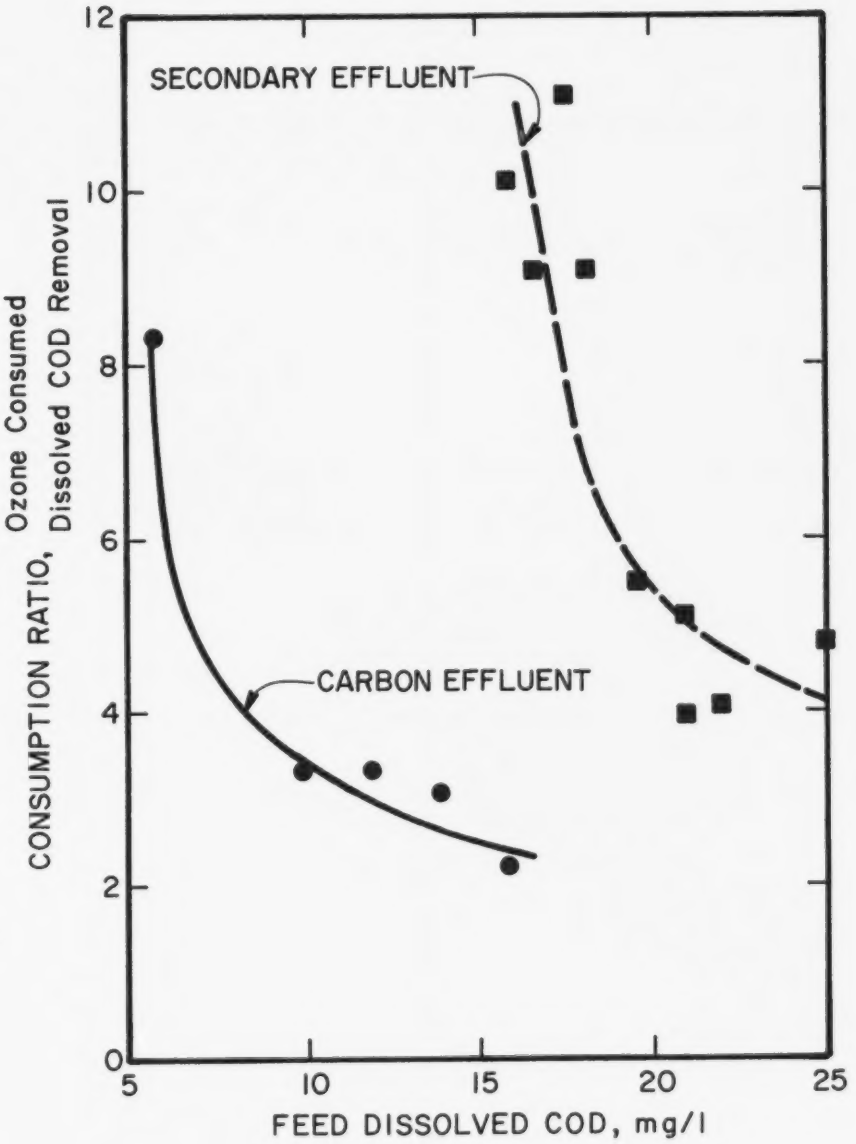


Figure 20 Ozonation consumption by the feed dissolved COD.

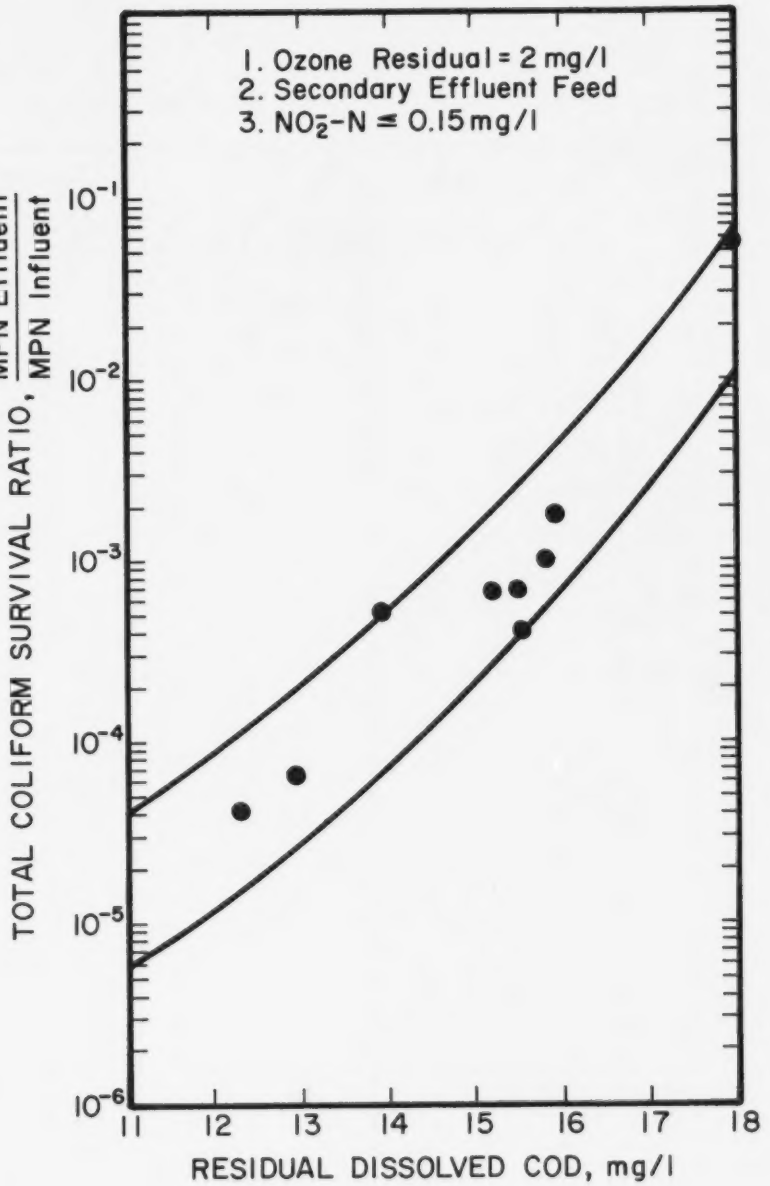


Figure 21 Residual DCOD effects on total coliform survival ratio in ozone disinfection.

Nitrite-N -- The relationship between nitrite and ozone is shown by the following equation:

$$NO_2^- + O \quad NO_3^- + O_2$$

Figure 22 shows an example of nitrite ozone reactions in secondary effluent. Ozone reacts with nitrite-N to form nitrates. A plot of estimated ozone consumption by the nitrite-N is shown in Figure 23. The figures were derived in the laboratory using deionized water containing sodium nitrite ($NaNO_2$) solution and in the pilot plant using secondary effluent. A higher consumption ratio was found for the secondary effluent than in the deionized water. Differences in the two ratios were due to increased ozone consumption resulting from materials in the secondary effluent

The effects of nitrites on ozone disinfection performance may be observed in experiments conducted with carbon filter effluent. Figure 24 is typical of the results. In carbon filter effluent samples, where the nitrite concentration was 1 mg/l or greater, disinfection was generally poor when the ozone dosage was 10 mg/l. However, when the nitrite level was less than 0.2 mg/l, effective coliform reduction was accomplished with an ozone dosage of less than 2 mg/l. To meet a total coliform standard of 2.2 MPN per 100 ml in carbon filter effluent would require a nitrite concentration of less than 0.15 mg/l for an ozone dosage of 10 mg/l. On the other hand, a nitrite concentration of 1.5 mg/l could be tolerated in meeting a fecal coliform standard of 200 MPN per 100 ml for the same ozone dosage.

Suspended Solids -- The ozone demand of suspended solids cannot be ignored. Suspended solids concentration has been described as an important parameter in disinfection. To understand the relationship between suspended solids and bacterial kill by ozone, a study was conducted using Ozonation System No. 3. The pilot plant was divided into two systems with one ozonator, one air dryer, and three contact chambers per system. Parallel streams of secondary effluent were passed through these chambers. The experiments were performed under identical operating conditions in order to obtain a valid comparison of the two results. Three of the columns were fed with air and three of the columns were fed with ozone at a dose of 3 mg/l. The gas/liquid ratio maintained in all columns was 1:10.

Figure 25 shows the suspended solids and turbidity removal in secondary effluent fed with ozone and with air. The total suspended solids and turbidity removal in the columns fed with ozone were 70 percent and 40 percent, respectively. By comparison, the total suspended solids and turbidity removal in the columns fed with air were 30 percent and 5 percent, respectively. The higher removals detected in the columns indicated that ozone oxidation may have been responsible for the suspended solids and turbidity reduction.

A brief study was conducted in the laboratory to confirm this assumption. A mixture of deionized water with a high suspended solids concentration was with deionized water containing ozone. No suspended solids could be detected in the mixture. Since no flotation mechanism was involved in the laboratory studies, the suspended solids removal was assumed to be due to ozone. This being the case, it is suspected that the bulk of the suspended solids in the effluents tested were organic in nature.

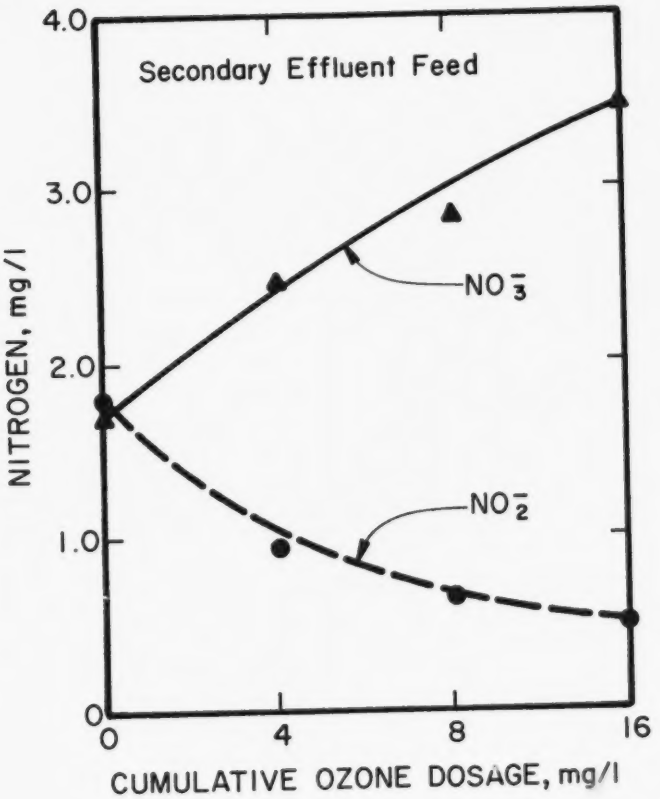


Figure 22 Nitrite oxidation reaction with ozone.

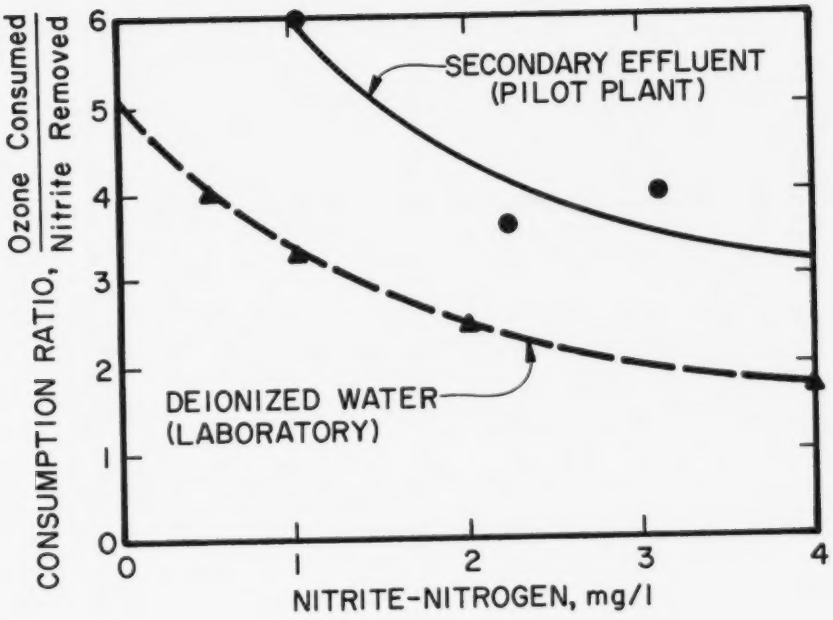


Figure 23 Ozone consumption by the nitrite in secondary effluent and deionized water.

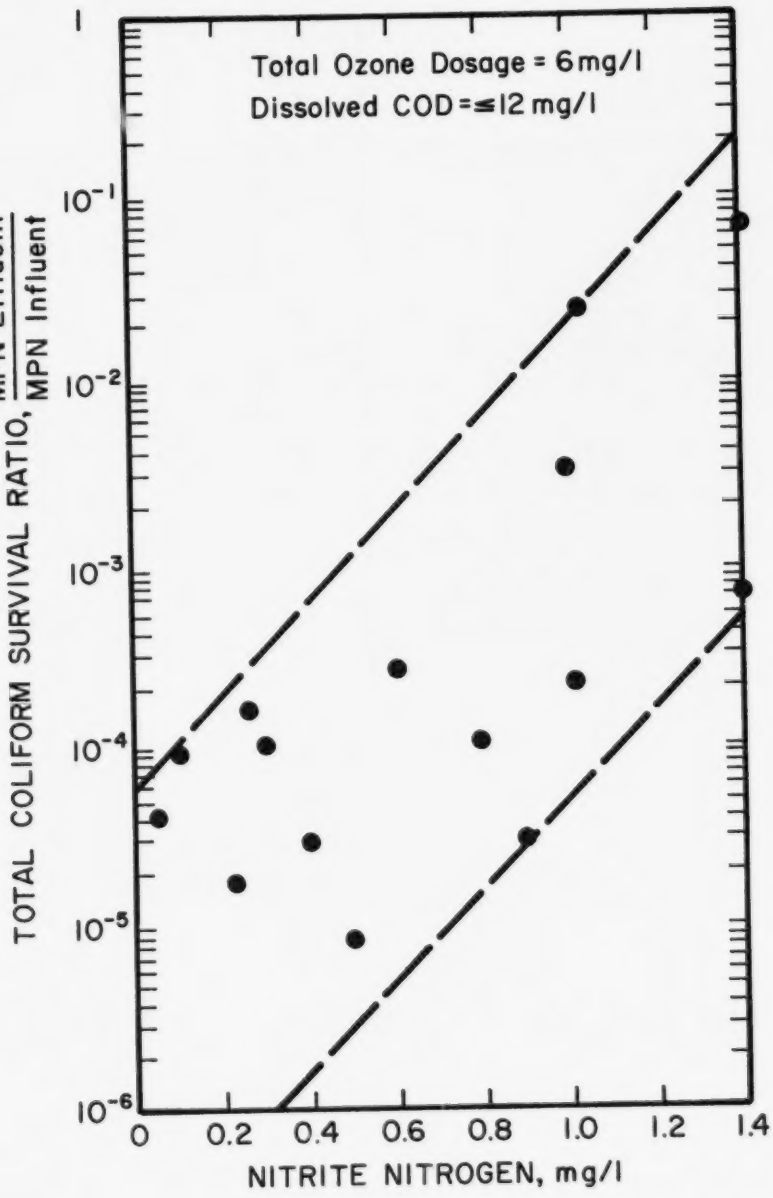


Figure 24 Nitrite-nitrogen influence on disinfection with ozone.

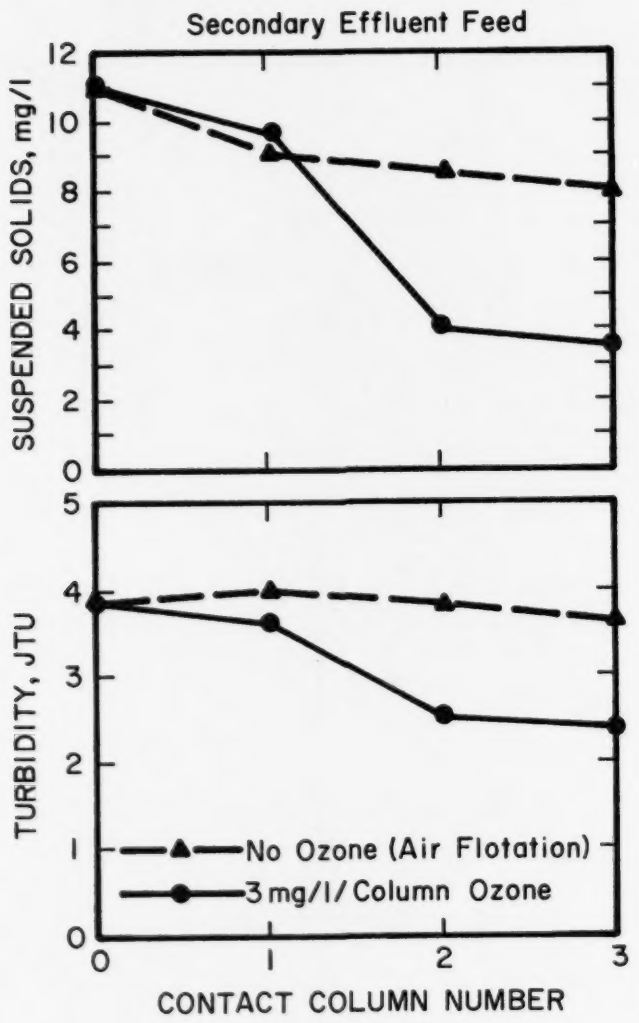


Figure 25 Suspended solids removal with ozone.

The effects of high (23 mg/l) and low (11 mg/l) suspended solids on disinfection with ozone are shown in Figure 26. With the exception of the suspended solids, these data were selected primarily for their similarity in water qualities -- particularly the soluble COD and nitrite concentrations. In the first two contact chambers, prior to complete removal of the suspended solids, there was a small coliform survival ratio difference in the two effluents. In contact chambers Nos. 3 thru 6, where most of the suspended solids had been removed, the coliform survival ratio difference was insignificant. These results suggest that filtration pretreatment may not always be necessary for ozone disinfection.

Color -- Ozone has been shown to be very effective in removing color from secondary effluent. Because ozone is consumed in removing color, its disinfection efficiency may be impeded by the color compounds in wastewater. Attempts were made to correlate influent color with coliform survival ratio after ozonation. However, the influent color in wastewater was found to vary with the influent soluble COD. Thus, the effects due to the influent soluble COD concentration could not be separated from the effects due to influent color and a direct correlation of color with coliform survival ratio could not be made.

Other Parameters Affecting Disinfection with Ozone --

The influence of ozone residual and contact time on ozone disinfection performance was not disregarded in the pilot plant studies. In the subsequent figures, note that the effects of these parameters on disinfection efficiency are closely related to the quality of the effluent. Given a good quality effluent (low in soluble COD and nitrite) sufficient coliform bacteria destruction can be achieved with a short contact period and a negligible amount of ozone residual.

Ozone Dosage/Residual -- The residual ozone concentration is a function of ozone dosage and the demand of a given wastewater effluent. Figure 27 shows a correlation between ozone dosage and residual for a secondary effluent and a carbon filter effluent. A smaller ozone dose was necessary in the carbon filter effluent to produce the same ozone residual as the secondary effluent. This was due to the lower concentration of ozone demanding substances found in the carbon filter effluent.

A relationship exists between the ozone residual and the coliform survival ratio in a given effluent as shown in Figure 28. A larger residual generally resulted in a lower coliform survival ratio. During the pilot plant studies, the ozone residual in the secondary effluent was found to have a much shorter life (less than 3 minutes) than in the carbon filter effluent. This may have been due to the presence of more ozone demanding substances in the secondary effluent which continually reacted with ozone, thereby, lowering the ozone residual. Therefore, the disinfection power of the residual would still be dependent on the ozone demanding substances present in the effluent.

Contact Time -- Contact time is known to be a criterion influencing the disinfection efficiency for most disinfectants. In the pilot plant

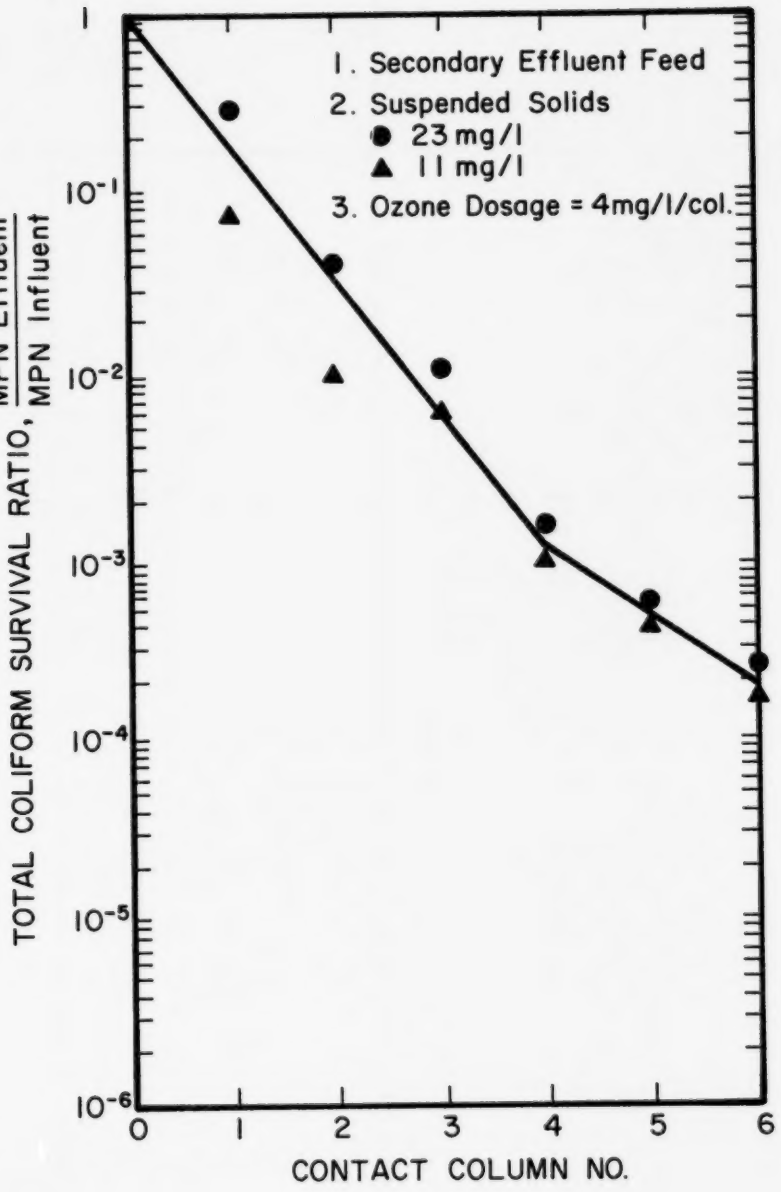


Figure 26 Ozone disinfection results of effluent with high and low suspended solids.

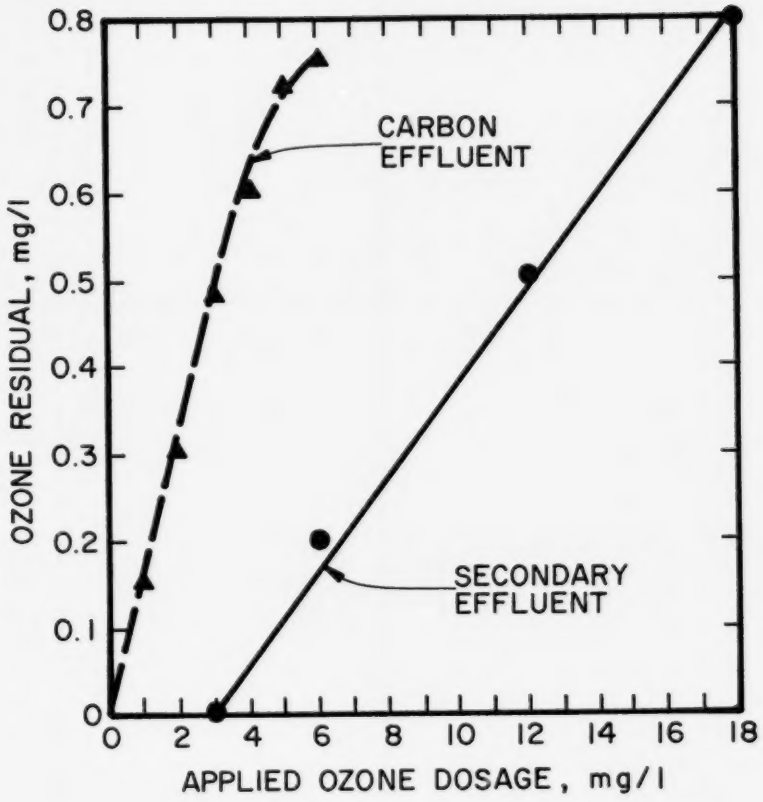


Figure 27 Relationship between ozone dosage and residual.

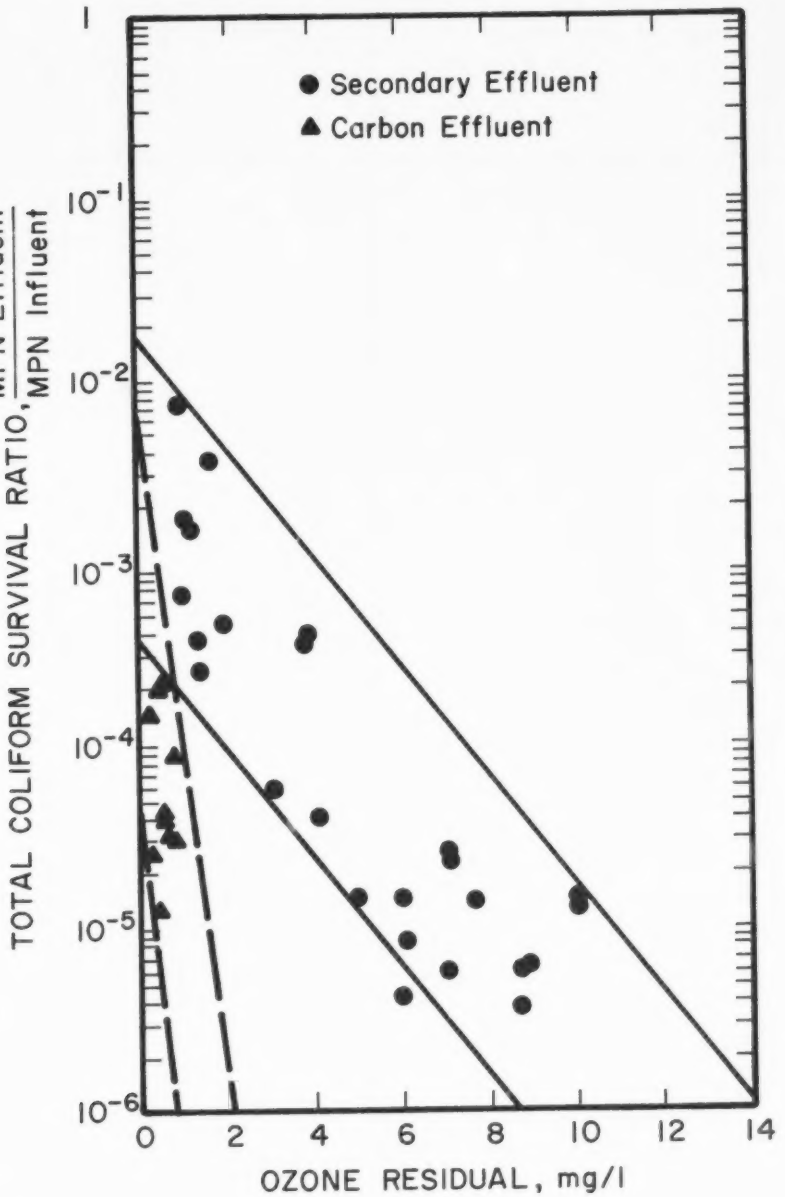


Figure 28 Ozone residual effects on disinfection with ozone.

studies, it was found that the contact time necessary for substantial disinfection with ozone was less than two minutes.

An ozone dosage of 12 mg/l was added to the respective effluent in the first contact column. Samples were collected for bacteriological analyses at two, four, and twelve minutes after ozone addition. As shown in Figure 29, 6 logs of coliform organisms, were eliminated after two minutes contact with ozone in the carbon filter effluent. Prolonging the contact time to twelve minutes increased the kill only slightly. The same was found for secondary effluent. Both results indicate ozone's efficacy as a disinfectant, especially in the first two minutes of contact. Beyond this time, ozone's effectiveness decreased probably because ozone was depleted in the formation of by-products (peroxides and ozonides). The effects of long detention times for ozone disinfection were also observed in the laboratory studies. Table 10 shows very little improvement in total coliform kill with a long detention time following ozonation.

The effective contact time of ozone should not be confused with the contact time provided in the contact chambers. In the above case, although a contact period of 12 minutes was provided, the effective contact time was only two minutes since ozone was injected in only one of the columns. A longer effective contact time is necessary for disinfection of secondary effluent which contained a large number of ozone demanding substances. In this study, an effective contact time of 12 minutes was obtained by injecting ozone through all six columns.

Ranking of Pretreatment Schemes

Pretreatment of wastewater prior to ozone disinfection has been found to significantly reduce ozone demand. During the pilot plant studies, several pretreated effluents were subjected to ozonation to determine if the results were in accordance with those found in phase 1. Eighteen experiments were performed for Scheme A and Scheme B, and 24 experiments for Scheme C. The studies for Scheme C, unlike the preceding experiments, were conducted in about the same period as for Schemes A or B, thus allowing a more justifiable comparison of their results. Schematics (see Figure 6) and operating parameters for the three treatment schemes were discussed earlier. An ozone dosage of 10 mg/l was utilized in Schemes A and B. The dosage was selected based on an equivalent estimated cost for the chlorination-dechlorination process. The 6 mg/l ozone dosage for Scheme C was selected based on results obtained in phase 1 of this study.

A summary of the total coliform results for the three pretreatment schemes, based on the percent of experiments meeting the disinfection standard, is shown in Figure 30. The results for Scheme C were divided into those with high nitrite (C_1) and those with low nitrite (C_2). The high nitrite was found on days when there was an upset in the activated sludge treatment plant. The low nitrite was found during normal operation of the plant.

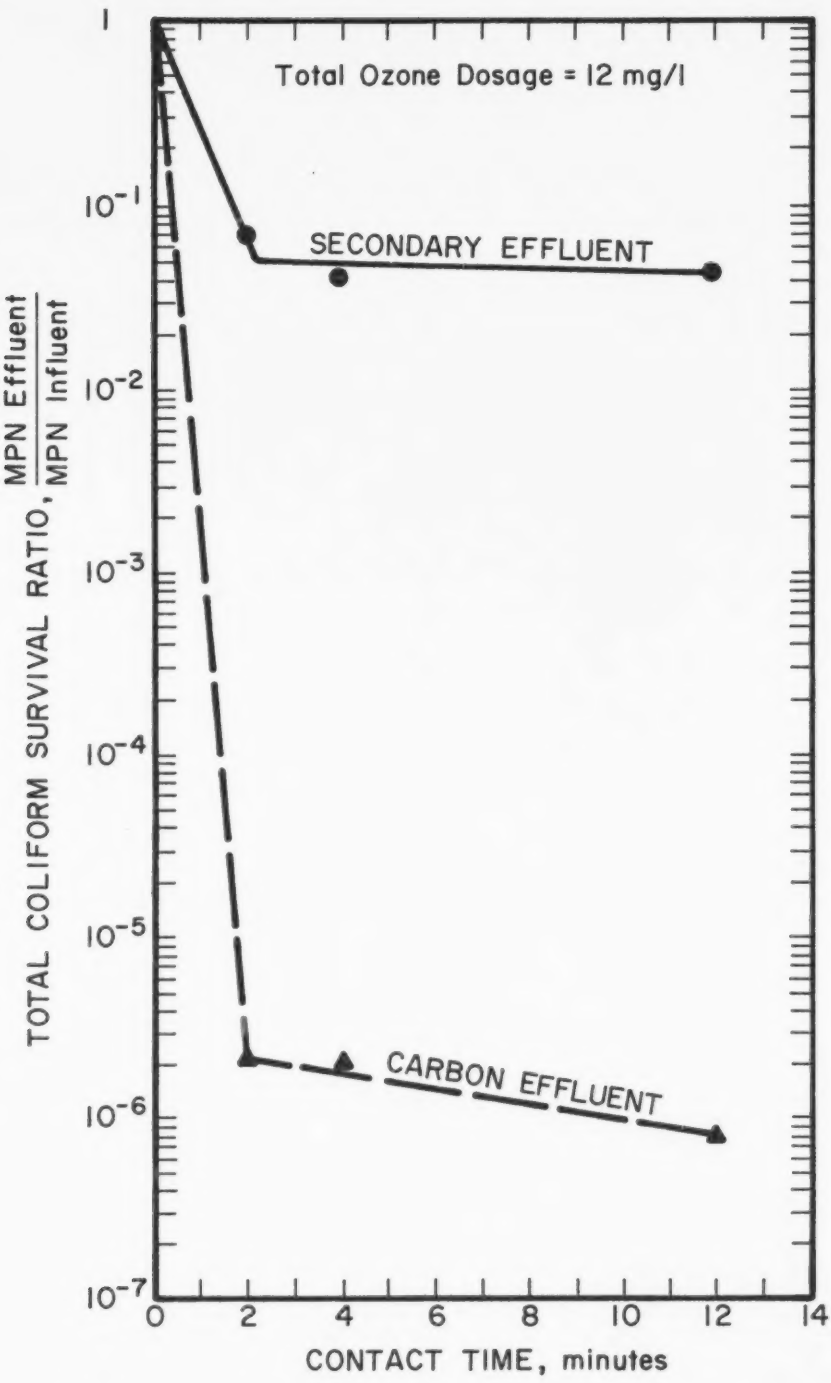


Figure 29 Contact time effects on disinfection with ozone for two effluents.

TABLE 10. EFFECTS OF HOLDING TIME ON OZONE DISINFECTION RESULTS

Total Coliform, MPN per 100 ml			
After Filter	After Ozone	After Ozone + 1 Hr Deten.Time	After Ozone + 2 Hr Deten.Time
2.2×10^4	7.0×10^2	7.0×10^2	4.9×10^2
4.9×10^4	1.3×10^2	1.3×10^2	49
3.3×10^4	4.9×10^2	4.9×10^2	3.3×10^2
7.0×10^4	23	49	23
4.6×10^4	33	2	3.5×10^2
7.9×10^4	8	4	11

NOTE: 1. Filter, Pressure (multi-media) w/loading rate of 10 gpm/ft^2, chemical addition consisted of Polymer WT-3000 of 0.1 mg/l and Alum of 10 mg/l

2. Ozone Consumption of 35 mg/l.

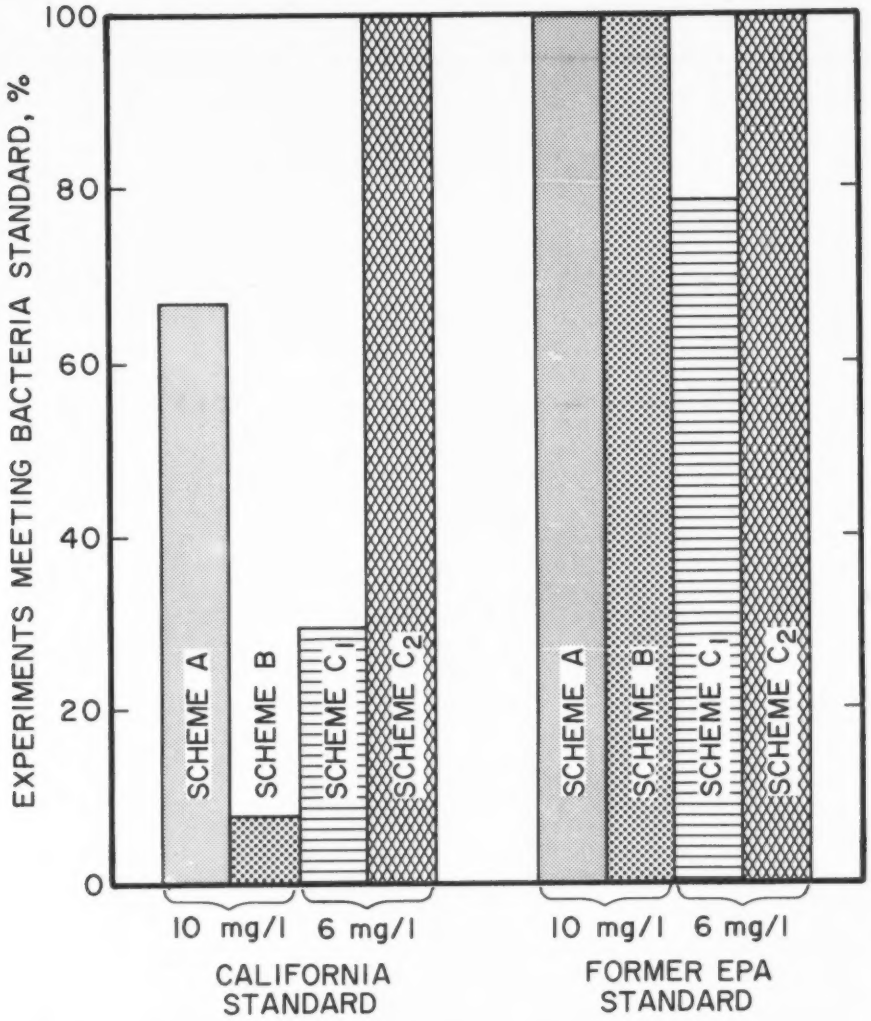


Figure 30 Probability of meeting disinfection standards with various pretreatment schemes.

Of the three schemes evaluated, Scheme C_2 met the California effluent coliform standard most regularly. Scheme A met the standard in 65 percent of the tests. Scheme C_1 met the standard in only 30 percent of the tests and Scheme B was capable of meeting the standard only 10 percent of the time.

As indicated in Table 11, the effluent which met the California disinfection standard most frequently had low nitrite in the pretreated effluent or low soluble COD in the ozonated effluent. Scheme C_2 had the least concentration of nitrite and soluble COD and was the treatment scheme which met the California standard consistently. Scheme B had the highest concentration of residual soluble COD and color. Therefore, the disinfection results for this effluent were the poorest of the three treatment schemes. Effluents from Schemes A and C had similar concentration of residual soluble COD but different levels of nitrite. These results are consistent with those found earlier.

The type of pretreatment applied to the secondary effluent was not significant in terms of meeting the EPA disinfection standard by ozonation. Referring to Figure 30, Schemes A, B, and C_2 met the disinfection goal in 100 percent of the experiments.

Virus Removal

Effects of ozone on virus were briefly investigated in conjunction with the California State sponsored project at the Advanced Wastewater Research Facility in Pomona. Experiments were performed both with seeded Polio Virus Type 1 and with naturally occurring virus. Seven experiments were conducted on each pretreatment scheme with both seeded and naturally occurring virus. The results of the virus seeding experiments for Schemes A, B, and C are plotted in Figures 31, 32, and 33. The results of the natural virus experiments for these schemes are summarized in Table 12.

The influence of wastewater constituents on the inactivation of polio virus was observed. A trend was found between the influent total COD and virus survival ratio in two of the schemes. The nitrite was at negligible level in these schemes and therefore did not exert an effect. A higher influent total COD often resulted in a higher virus survival ratio in the ozonated effluent. This was observed in nearly all the runs, as shown in Figures 31 and 32, for Schemes A and B, respectively. In Scheme C (Figure 33), the virus survival ratio response did not seem to be related to the influent total COD.

Referring to Figure 31, the deviation in response of virus from the total COD in Experiment No. 5 may be attributed to a drop in the nitrite concentration. The influence from nitrite on virus inactivation is also observed in Scheme C (Figure 33). Nitrite concentrations in these experiments were especially high (greater than 1 mg/l). The high influent nitrites appeared to have superseded the total COD effects on virus inactivation.

The natural virus results (Table 12) are more difficult to interpret. This is because no virus were detected in the secondary effluent in many of the experiments. In general, approximately 1 to 3 log virus removal was found through the whole treatment scheme. A higher log removal was found for the better quality secondary effluent.

TABLE 11. CHARACTERIZATION OF PRETREATED AND OZONATED EFFLUENTS

PARAMETER	PRETREATED EFFLUENT				OZONATED EFFLUENT			
	A	B	C_1	C_2	A	B	C_1	C_2
Soluble COD	19	21	17	9	14	16	14	7
NO_2-N, mg/l	0.2	0.3	1.1	0.1	0.1	0.1	0.6	0.1
Color, units	19	26	14	7	4	5	5	1
Suspended Solids, mg/l	1	2	2	2	1	1	2	0.2
pH	6.8	7.3	7.4	7.7	7.2	7.5	7.7	7.8
Temp. ^oC	25	25	25	25	25	25	25	26
Ozone Dosage mg/l	--	--	--	--	10	10	6	6
No. of Experiments	18	18	14	10	--	--	--	--

NOTES: 1. For a description of A, B, and C, see Figure 6.

2. C is divided into C_1 (high nitrite) and C_2 (low nitrite).

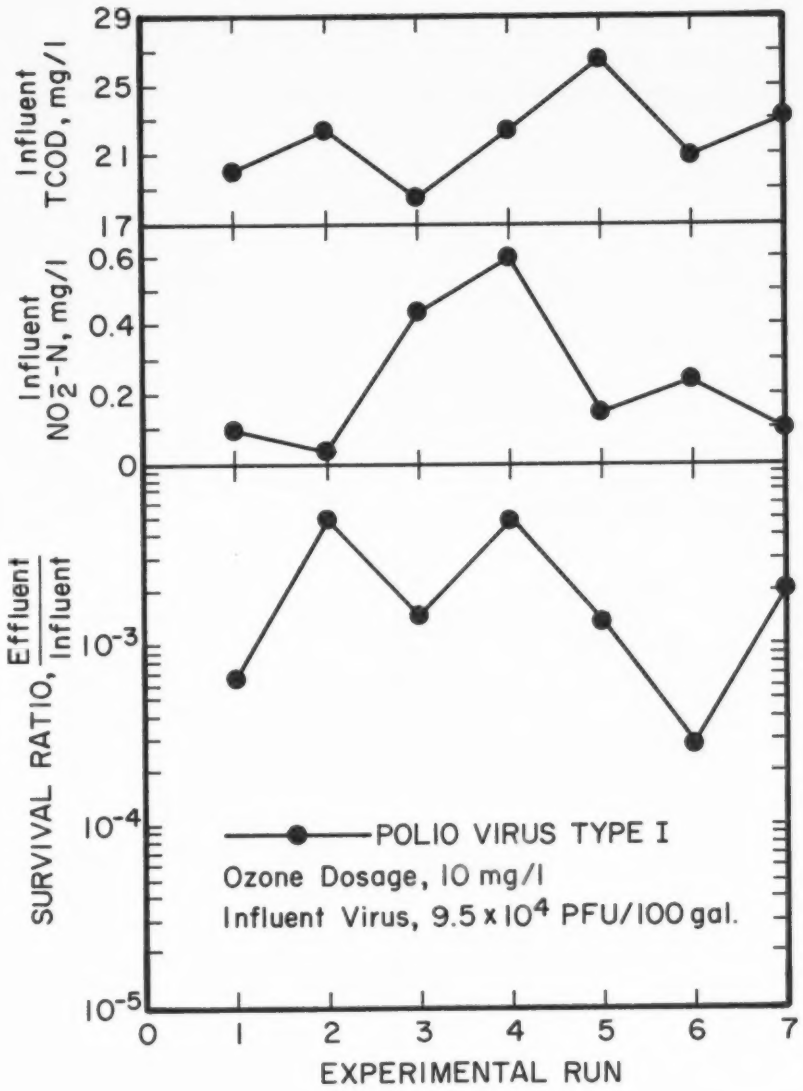


Figure 31 Virus seeding results for scheme A.

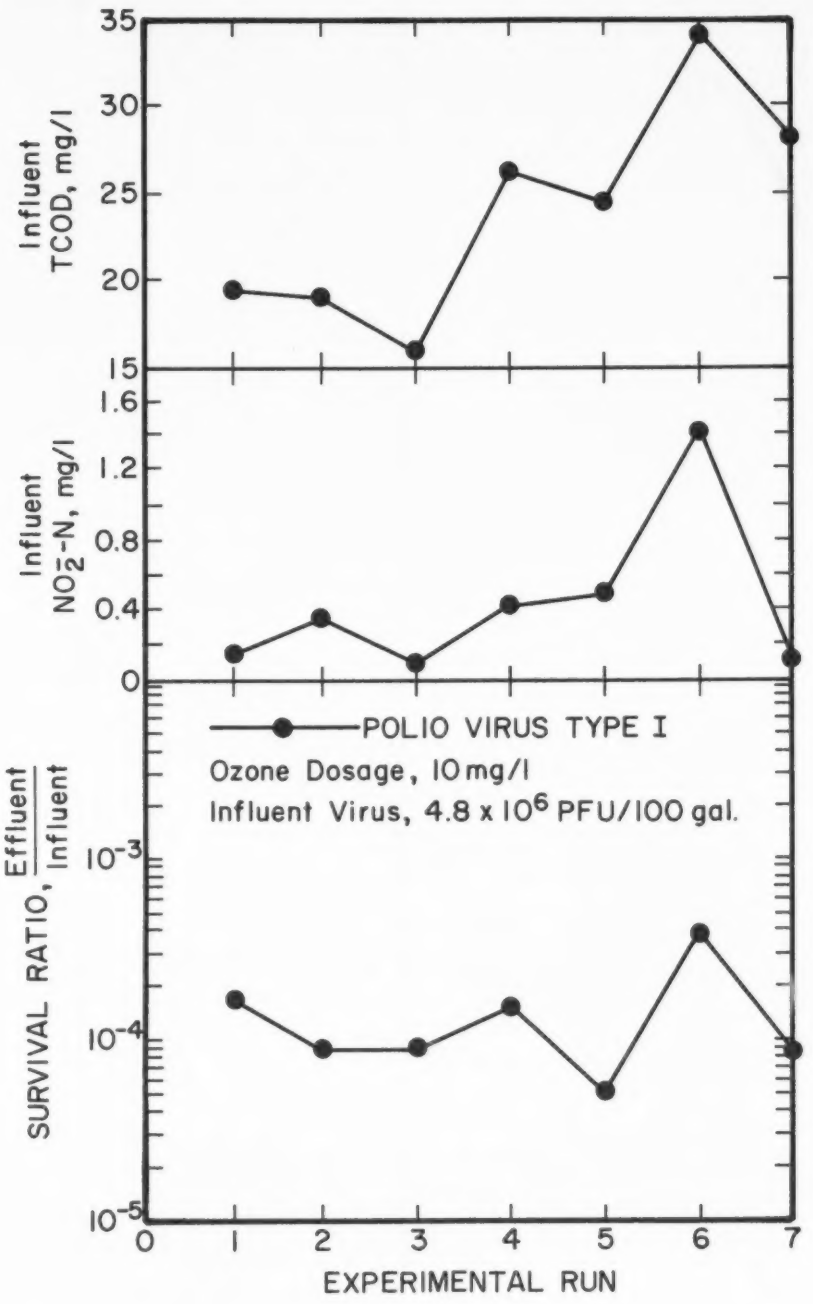


Figure 32 Virus seeding results for scheme B.

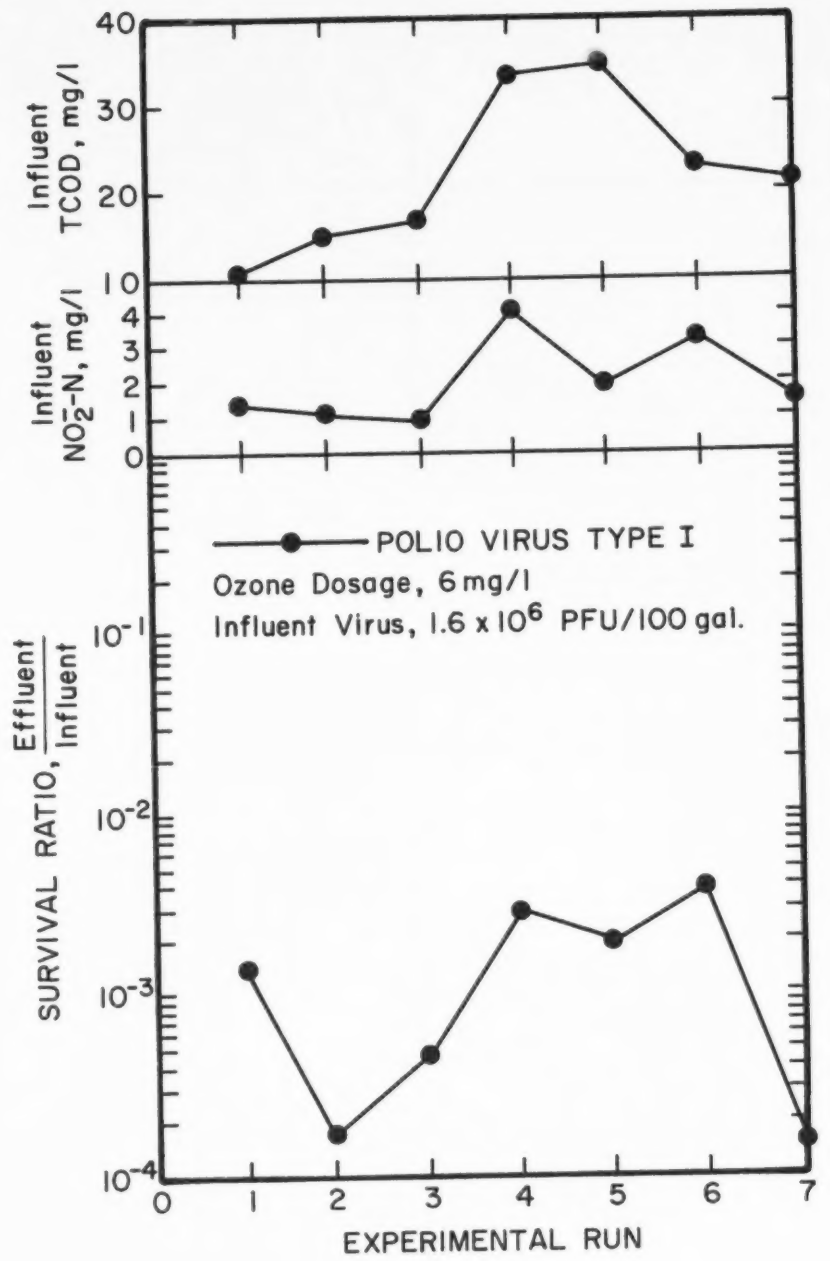


Figure 33 Virus seeding results for scheme C.

TABLE 12. POMONA NATURAL VIRUS STUDIES WITH OZONE

System-Disinfectant	Date	Major Water Quality Parameters				Natural Virus Concentration			
		Secondary Effluent		Final Effluent		Secondary Effluent		Final Effluent	
		DCOD, mg/l	NO_2^--N, mg/l	DCOD, mg/l	NO_3^--N, mg/l	PFU/100 gal	Types Recovered	PFU/100 gal	Types Recovered
A-O_3	9/ 3/75	23	0.85	11	0.05	710	Reo, Polio 1	0	None
A-O_3	9/ 4/75	21	0.45	15	0.10	1390	Polio 1	71	Reo ECHO 1, Polio 3
A-O_3	9/11/75	22	0.10	12	0.05	N.P.	ECHO 1	0	None
A-O_3	10/21/75	22	0.28	12	0.45	2170	Polio 1	N.P.	Polio 1
A-O_3	10/22/75	20	0.10	18	0.10	N.P.	Polio 1	0	None
A-O_3	11/ 5/75	22	0.49	13	0.10	N.P.	Polio 2	0	None
A-O_3	12/ 5/75	25	0.25	15	0.05	N.P.	Polio 1	N.P.	Polio 1
B-O_3	9/ 9/75	21	0.10	13	0.05	260	Polio 1,3	N.P.	Polio 1
B-O_3	9/10/75	21	0.05	16	0	0	None	65	ECHO 1
B-O_3	9/12/75	22	0.05	17	0.05	840	ECHO 1, Polio 1,2,3	0	None
B-O_3	9/19/75	18	0.05	14	0.05	0	None	0	None
B-O_3	10/27/75	22	0.23	13	0.09	0	None	0	None
B-O_3	10/31/75	27	0.10	17	0.05	0	None	0	None
B-O_3	11/ 3/75	31	0.25	16	0.10	N.P.	ECHO 1	0	None
C-O_3	9/25/75	22	0.10	8	0.10	0	None	0	None
C-O_3	10/23/75	23	0.25	11	0.10	0	None	0	None
C-O_3	10/28/75	22	0.70	11	0.09	0	None	0	None
C-O_3	11/ 4/75	22	0.25	11	0.10	0	None	0	None
C-O_3	11/ 6/75	23	0.25	-	0.25	0	None	0	None
C-O_3	11/10/75	19	0.05	13	0.05	0	None	0	None
C-O_3	12/18/75	30	0.40	17	0.10	4200	Polio 1	305	Polio 2

N.P. = Virus detected in tube assay but no plaques formed.

OTHER APPLICATIONS OF OZONE

Improvement of Sand Filter Performance

Figure 34 shows a summary of the operating parameters for the sand filter pretreatment studies. One of the filters (Filter No. 1) was fed with ozonated secondary effluent and the other (Filter No. 2) was fed with non-ozonated secondary effluent. Their results are summarized in Table 13.

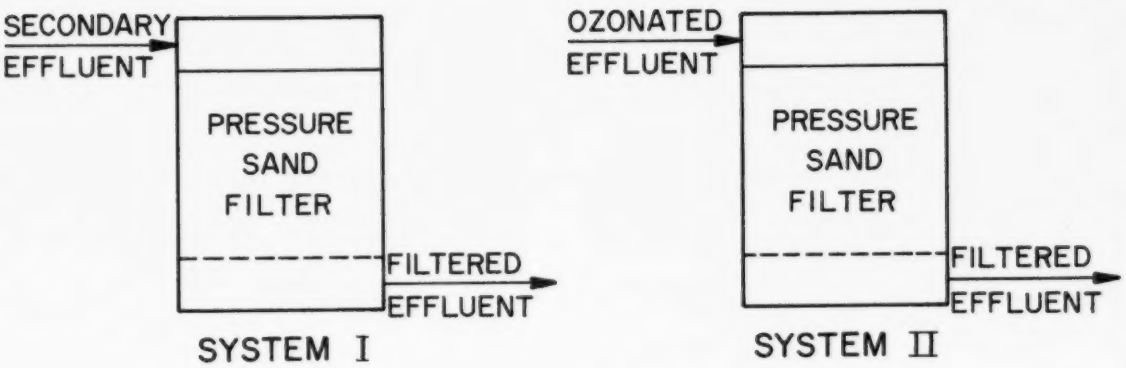
Referring to the table, suspended solids and turbidity removal were generally better in the pre-ozonated filter. Headloss in Filter No. 1 was also considerably lower than in Filter No. 2. During backwash of Filter No. 1 fine dark residues, possibly by-products of ozone reactions with the suspended materials were noticed. Globules or agglomeration of flocculant matter from the secondary effluent were, however, found in Filter No. 2.

Bacterial recontamination of the ozonated effluent was observed in Filter No. 1. Table 14 shows a summary of the results. An increase in total coliform numbers varying from 1 to 3 logs was found.

Because of poor filter performance and contamination of the ozonated effluent, it was of interest to observe the results of adding ozone was subsequent to filtration instead of prior to filtration. Of particular interest was the effluent quality when a small dose of alum (10 mg/l) and polymer (0.1 mg/l Calgon WT-3000) was added before filtration and ozonation. Any contamination of the effluent would also be avoided by this method of application. Table 15 shows a summary of the results. A reduction of the turbidity by about 1 JTU and some removal of suspended solids were observed after ozonation of the filtered effluent. The total coliforms in the effluent from this scheme were lower than the effluent from previous flow schemes. Therefore, the injection of ozone after filtration seemed to be a better alternative than before filtration.

Improvement of Carbon Filter Performance

A study by the Cleveland Regional Sewer Districts showed that organic compounds in effluent pretreated with ozone adsorbed more readily to carbon than untreated effluent. Accordingly, it was of interest to determine if similar advantanges could be obtained using ozone as a pretreatment for carbon filtration of Pomona Water Reclamation Plant effluent. A small bench-scale system from previous pilot plant studies was used for the carbon studies. Figure 35 shows a schematic diagram of the system. The four columns in the system were divided into two pairs of columns. The first two columns (System I) were operated in series and in a downflow mode. It was fed with secondary effluent. The second two columns (System II) were operated in a similar manner and were fed with ozonated secondary effluent. Detention time in both systems was 26 minutes at a hydraulic loading rate of 3.4 gpm/ft^2. The ozone dosage in System II was 10 mg/l. Both systems were operated 24 hours per day, 5 days per week. At the end of 5 days, the carbon was backwashed thoroughly. It was not operated during the weekend primarily because there was no operating personnel at the research facility. The period between backwashes was 5 days because initial tests had shown this period to be necessary for the headloss to build to any significant level.



PARAMETER	SYSTEM I	SYSTEM II
Feed Source	Secondary Effluent	Ozonated Effluent
Flow, gpm	7 gpm	Same
Ozone Dosage, mg/l	0	10
Dimension	20" dia x 32" depth	Same
Loading Rate, gpm/ft^2	3	Same
Backwash	Every 4 days @ 6 gpm/ft^2 for 15 min.	Same

Figure 34 Operating parameters of filter pretreatment studies.

TABLE 13. EFFECT OF OZONE PRETREATMENT ON FILTER EFFICIENCY

Parameter	Secondary Effluent	With Ozone Pretreatment[1]			Without Ozone Pretreatment	
		After Ozonation	After Ozonation & Filtration	Total Removal (%)	After Filtration	Total Removal (%)
Suspended Solids (mg/l)	10.0	7.7	3.2	68.0	4.6	54.0
Turbidity (JTU)	9.6	7.1	3.1	67.7	4.9	49.0
Headloss (psig)	-	-	4.1	-	10.0	-
Color (units)	39.5	7.6	6.0	84.8	-	-
Ammonia-N (mg/l)	21.4	21.4	20.3	-	23.2	-
Nitrite-N (mg/l)	0.8	0.2	1.0	-	0.8	-
Nitrate-N (mg/l)	0.9	1.3	1.2	-	0.3	-
Total COD (mg/l)	36.4	31.8	28.4	-	35.8	-
Soluble COD (mg/l)	32.7	28.3	27.0	-	31.1	-
Diss. Oxygen (mg/l)	2.6	8.7	5.8	-	0.4	-
pH	7.6	7.6	7.4	-	7.6	-
Temperature (°C)			22.0			

[1]Ozone Consumption = 18 mg/l.

TABLE 14. EFFECTS ON DISINFECTION RESULTS OF FILTER WITH OZONE PRETREATMENT

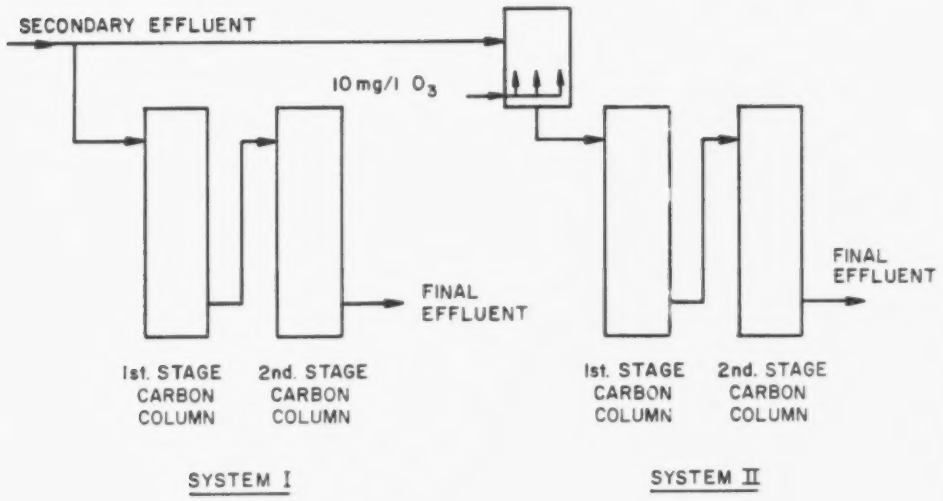
Total Coliform, MPN per 100 ml		
Sec. Effluent	After O_3	After O_3 + Filter
1.7×10^5	1.3×10^3	4.4×10^4
3.3×10^5	2	1.5×10^4
3.3×10^4	1.3×10^2	4.0×10^3
1.7×10^6	1.3×10^2	2.3×10^3
1.3×10^5	1.7×10	1.3×10^4
2.4×10^6	2.3×10^2	2.3×10^3
4.9×10^5	1.1×10^2	1.3×10^3
2.3×10^5	4.9×10	1.1×10^4

TABLE 15. OZONATION EFFECTS ON CHEMICALLY PRETREATED FILTERED EFFLUENT

Parameter	Secondary Effluent	After Chem. Inject./ Filtration	After Chem. Inject./ Filtration/Ozonation
Suspended Solids, mg/l	8.7	4.3	4.0
Turbidity, JTU	7.4	4.5	3.3
Dissolved Oxygen, mg/l	3.9	-	7.7
pH	7.3	-	7.3
Total Coliform, MPN/100 ml	3.3×10^5	-	7.0×10^2
Temp. ^oC		23	

NOTE: 1. Pressure (multi-media) filter w/loading rate of 10 gpm/ft^2 and Det. Time of 4 mins. Chemical Dose consist of Polymer WT-3000 (0.2 mg/l) and Alum (10 mg/l).

2. Ozone Consumption of 18 mg/l.



Parameter	System I	System II
Feed Water	Secondary Effluent	Ozonated Effluent
Flow, gpm	0.3	0.3
Carbon Type	Filtrasorb-300	Filtrasorb-300
Surface Area, sq in	12.6	12.6
Carbon Depth, in	72	72
Empty-Bed Detention Time, min	26	26
Hydraulic Loading, gpm/sq ft	3.4	3.4
Number of Stage	2	2

Figure 35 Operating parameters of carbon pretreatment studies.

Parameters monitored during operation of the pilot plant systems were soluble COD, suspended solids, and headloss. The soluble COD, which is an indicator of soluble organic content in the wastewater, measures the performance efficiency and, hence, regeneration requirement of the carbon. The headloss, which is caused by a buildup of suspended matter in the carbon column, determines the backwash frequency of the carbon. The suspended solids shows the extent of solids loading in the carbon. The results presented are based on a cumulative flow of 32,000 gallons and a cumulative organic loading of 0.6 lb soluble COD/lb carbon.

The main advantage of pretreating the effluent with ozone is the slower headloss buildup in the carbon columns. Ozone effectively reduces the influent suspended solids, hence preventing a rapid increase of headloss through the carbon columns. Figure 36 shows the influent suspended solids and headloss as a function of the operating period for System I (secondary effluent) and System II (ozonated secondary effluent). The lower influent suspended solids in System II is probably due to ozone treatment. It has been found that ozone oxidizes and solubilizes some of the suspended matter in wastewater. The remaining suspended solids seems to exert little headloss in the carbon columns after 5 days of operation.

Another advantage found was the absence of sulfide formation in the carbon columns. This may be due to high oxygen content of the ozonated effluent. High oxygen is conducive to aerobic growth in the carbon columns and probably discourages any sulfide formation in the carbon columns.

With respect to soluble organics removal, the data do not seem to show any increase in carbon adsorption capacity. Figure 37 shows carbon adsorption performance of the two systems. The cumulative soluble COD removed (by weight) is plotted as a function of cumulative soluble COD loading (by weight), both per unit weight of carbon. The adsorption performance of the carbon fed secondary effluent and that fed ozonated effluent was quite similar in the initial stage up to 0.2 lb soluble COD/lb carbon loading. Beyond this point, breakthrough of the carbon in both systems was observed. The ozonated effluent seemed to produce breakthrough more quickly than the secondary effluent. The reason for this behavior is not known. A brief analysis of the effluents from both systems using a HIAC particle counter showed a decrease in particle concentration larger than 5 microns and an increase in particle concentration smaller than 5 microns after ozonation. This being the case, it appears that the larger particles were broken down into smaller particles during ozonation. The smaller particles were transported through the carbon bed more quickly than the larger particles. The presence of these minute by-products of ozonation may have impeded the carbon adsorption process and reduced soluble COD removal.

The effluent qualities of both systems were similar with the exception of the nitrogenous compounds and pH. Table 16 shows a summary of the effluent quality produced by both systems. System I had most of its color, suspended solids, and turbidity removed by carbon filtration. In System II these parameters were reduced by ozonation. Very little additional removal of these parameters occurred through the carbon columns. These refractory substances appear to resist both ozonation and carbon filtration.

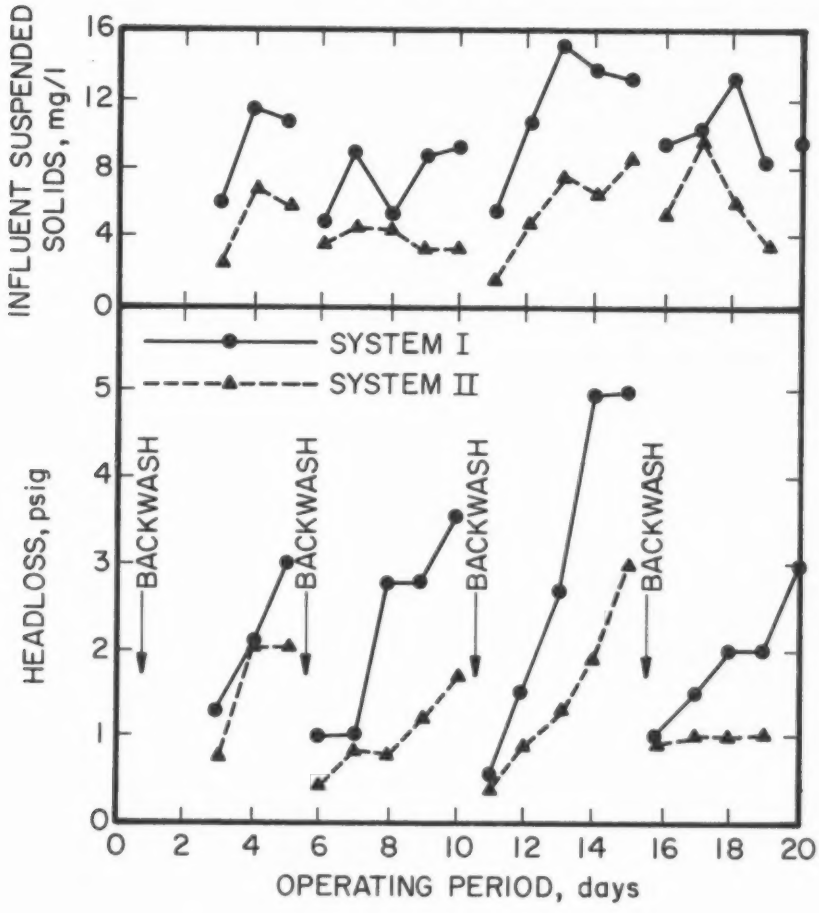


Figure 36 Filter pretreatment with ozone.

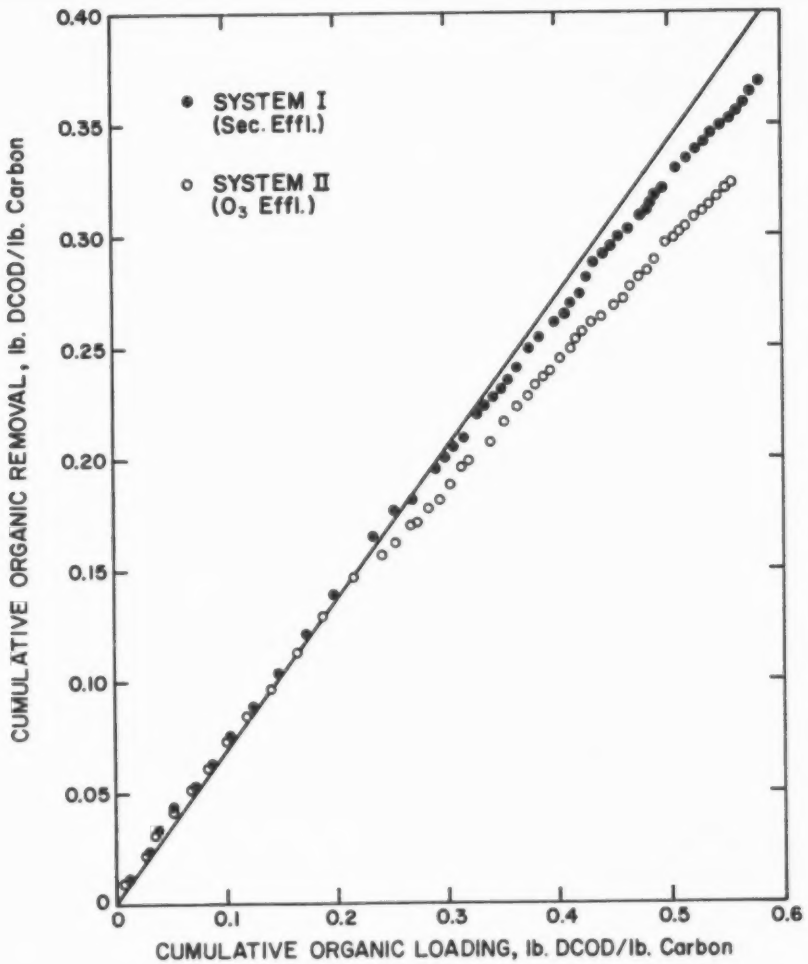


Figure 37 Adsorption curves of carbon fed with secondary and ozonated effluent.

TABLE 16. WATER QUALITIES OF SYSTEMS I AND II*

Parameters	Influent		After 1st Stage		After 2nd Stage	
	System I	System II	System I	System II	System I	System II
Color, units	14	3	8	3	3	2
Suspended Solids, mg/l	10	5	2	3	2	2
Turbidity, FTU	4	2	1	2	1	1
NH_3-N, mg/l	16	16	16	15	17	14
NO_2-N, mg/l	1.1	.06	0.5	0.9	0.2	1.1
NO_3-N, mg/l	1.9	2.4	1.0	2.2	0.8	2.1
pH	7.6	7.6	7.5	7.4	7.6	7.3
Temperature, ^oC			22			

* Based on 17-day average

SECTION 6

COST ESTIMATES

Cost estimates for an ozonation system were developed for a 10 MGD plant. This capacity plant was selected because the County Sanitation Districts were considering using ozone at the 10 MGD Pomona Water Reclamation Plant.

Estimates were made for various ozone dosages ranging from 12 to 72 mg/l. The cost of ozone generating equipment was obtained from PCI. The estimates are comparable to the costs provided by other ozone manufacturers.

Both oxygen-feed and air-feed systems were considered in the estimates. Table 17 shows the estimates derived for an air-feed system. Table 18 shows the estimates derived for an oxygen-feed system without any oxygen recycling equipment. Table 19 shows the costs for an oxygen-feed system with various percentages of recycled oxygen.

The ozonation cost at various percentages of recycled oxygen is shown in Figure 38 as a fraction of the cost of an air-feed system. As shown in the figure, for the range of ozone dosage investigated, the ozonation cost for any oxygen-feed system with no consideration for oxygen recycling is about 1.5 times higher than the cost for an air-feed system. The incorporation of oxygen recycling (2 to 47 percent) into the system reduced the cost to levels competitive with the air-feed system. These data show the economic value of oxygen recycling in an oxygen-feed ozonation system.

The savings in an oxygen-feed ozonation system originate from a reduction in ozone generation equipment. Twice as much ozone can be produced from oxygen than from air with the same generating system. Other assumptions made in obtaining the cost estimates are as follows:

1. The generator was capable of producing two percent ozone by weight from air and four percent ozone by weight from oxygen.

2. A multistage (six stage) contacting system with spargers was utilized.

3. Capital costs were amortized at an annual discount rate of 10 percent over a period of 15 years.

TABLE 17. OZONATION COST FOR A 10 MGD PLANT USING AIR FEED

Total Reqd., lbs/ O_3/day	1000	2000	3000	4000	5000	6000
Ozone Dose, mg/l	12	24	36	48	60	72
Capital Cost, $						
Ozonator/Air Prep. Equip.	770	1400	1900	2300	2800	3200
Contact System Incl. Excav., Sitework, Concrete & Steel	26	35	46	52	59	59
Subtotal	796	1435	1946	2352	2859	3259
Miscellaneous pumps, piping, etc. (20% of Subtotal)	159	287	389	470	572	652
Total	955	1722	2335	2822	3431	3911
Contractor's overhead & Profit (@ 15%)	143	258	350	423	515	587
Total	1098	1980	2685	3245	3946	4498
Contractor's Conting. (@ 10%)	110	200	270	330	400	450
Total	1208	2180	2955	3575	4346	4948
Capital Amortization (10% for 15 yrs)	159	287	387	470	571	651
Ozone Dose, mg/l	12	24	36	48	60	72
Operation and Maintenance Cost						
Electric Power (13 kwh/lb O_3 @ 3c/kwh)	143	285	427	569	712	954
Maintenance	6	6	6	12	12	12
Total	149	291	433	581	724	866
Total Ozone Cost	308	578	822	1051	1295	1517
c/1000 gal	8.5	15.9	22.6	28.9	35.6	41.7
c/liter	2.2	4.2	6.0	7.6	9.4	11.0

TABLE 18. OZONATION COST FOR A 10 MGD PLANT USING OXYGEN FEED (NO RECYCLING)

Total Reqd., lbs/ O_3/day	1000	2000	3000	4000	5000	6000
Ozone Dose, mg/l	12	24	36	48	60	72
Capital Cost, $						
Ozonator	456	750	930	1130	1300	1500
Contact System Including excavation sitework, concrete and steel	26	35	46	52	59	59
Subtotal	482	785	976	1182	1359	1559
Miscellaneous pumps, piping, etc. (20% of Subtotal)	96	157	195	236	272	312
Total	578	942	1171	1418	1631	1871
Contractor's overhead & Profit (@ 15% of above	87	141	176	213	245	281
Total	665	1083	1347	1631	1876	2152
Contractor's Conting. (@ 10% of above)	67	108	135	163	188	215
Total	732	1191	1482	1794	2064	2367
Capital Amortization (10% for 15 yrs)	96	156	195	236	271	311
Ozone Dose, mg/l						
Operation and Maintenance Cost						
Electric Power	66	131	197	263	329	394
(6 kwh/lb O_3 @ 3c/kwh)						
Oxygen incl. tanks and vap (@$70/ton)	320	640	960	1280	1600	1920
Maintenance	6	6	6	12	12	12
Total	392	777	1163	1555	1941	2326
Total Ozone Cost	488	933	1358	1791	2212	2637
¢/1000 gal	13.5	25.8	37.5	49.5	61.1	72.8
¢/k	3.6	6.8	9.9	13.1	16.1	19.2

TABLE 19. OZONATION COST FOR A 10 MGD PLANT USING OXYGEN FEED (WITH RECYCLING)

Total Reqrd., lbs O_3/day	1000	2000	3000	4000	5000	6000
Ozone Dose, mg/l	12	24	36	48	60	72
Capital Cost, $						
Ozonator	456	750	930	1130	1300	1500
Contact system incl., excav., sitework, conc., and steel	26	35	46	52	59	59
Subtotal	482	785	976	1182	1359	1559
Misc.Incl.,pumps, piping (@ 35% of above)	169	275	342	414	476	546
Total	651	1060	1318	1596	1835	2105
Contractor's Overhead & profit (@ 15%)	98	159	198	239	275	316
Total	749	1219	1516	1835	2110	2421
Contractor's Conting. (@ 10%)	75	122	152	184	211	242
Total	824	1341	1668	2019	2321	2663
Capital Amort. (10% for 15 yrs)	108	176	219	265	305	350

(continued)

TABLE 19 (continued)

Total Recycl. lbs O_3/day	1000	2000	3000	4000	5000	6000
Ozone Dose, mg/l	12	24	36	48	60	72
Operation and Maint. Cost						
Electric Power	66	131	197	263	329	394
(6 kwh/lb O_3 @ 3¢/kwh)						
Maintenance	6	6	6	12	12	12
Oxygen ($70/ton)						
10% Recycl.	128	256	384	512	640	768
50% Recycl.	26	51	77	102	128	153
75% Recycl.	17	34	51	68	85	102
Total (10% Recycl)	242	438	609	789	957	1130
Total (50% Recycl)	140	233	302	379	445	515
Total (75% Recycl)	131	216	276	345	402	464
¢/1000 gal (10% Recycl)	6.7	12.0	16.8	21.7	26.3	31.1
¢/1000 gal (50% Recycl	3.9	6.4	8.3	10.4	12.2	14.2
¢/1000 gal (75% Recycl)	3.6	5.9	7.6	9.5	11.1	12.8
¢/ℓ (10% Recycl)	1.8	3.2	4.4	5.7	6.9	8.2
¢/ℓ (50% Recycl)	1.0	1.7	2.2	2.7	3.2	3.8
¢/ℓ (75% Recycl)	0.9	1.6	2.0	2.5	2.9	3.4

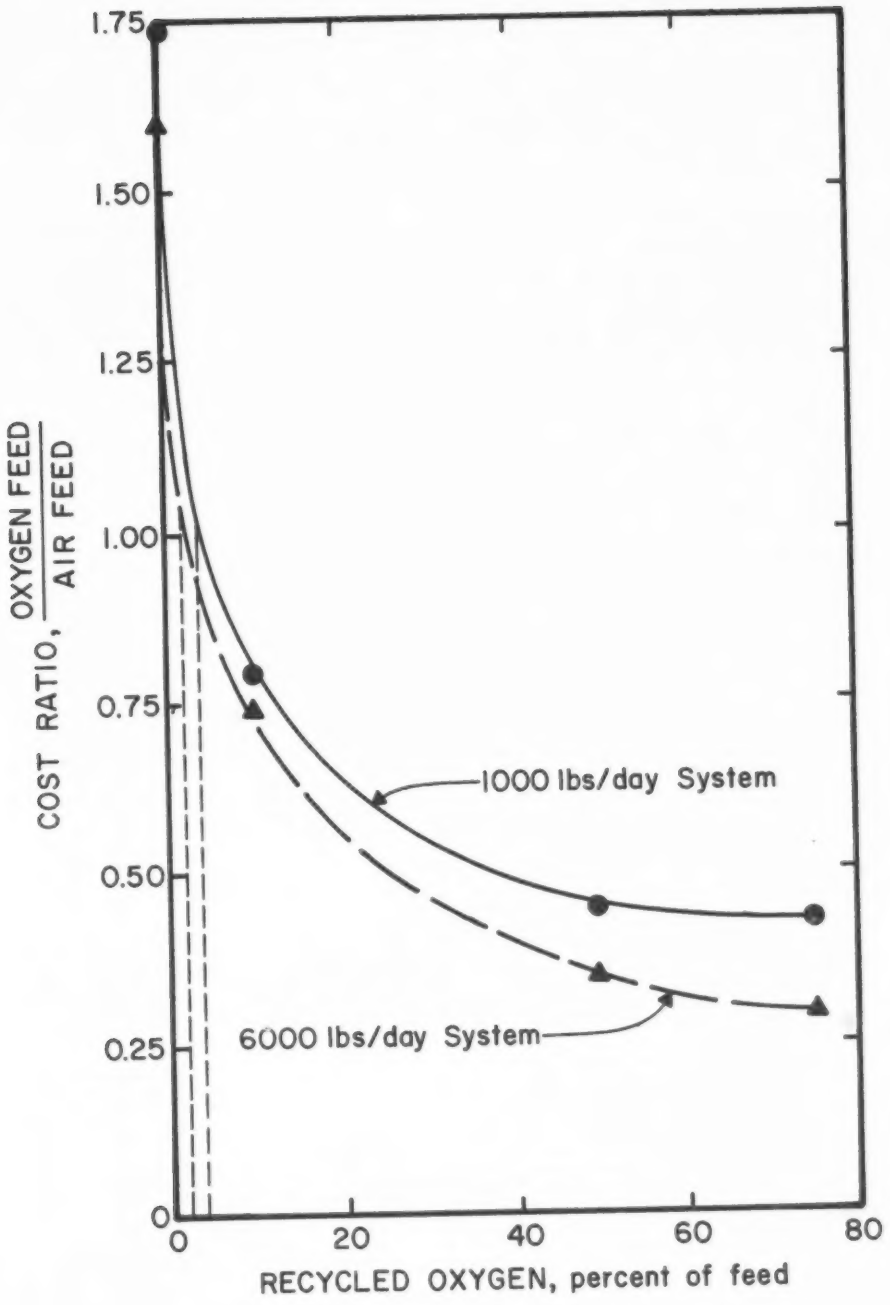


Figure 38 Cost relationship between an oxygen feed and air feed ozonation system.

4. The electrical energy requirement for the ozonation system was 6 kWh/lb O_3 for the oxygen-feed system and 13 kWh/lb O_3 for the air-feed system. Electricity cost was assumed to be 3 cents/kWh.

5. The liquid-oxygen cost was $70/ton including storage tanks and vaporizers.

6. Miscellaneous accessories such as pumps and piping were estimated to be 20 percent of the capital cost with no oxygen recycling equipment and 35 percent of the capital cost with oxygen recycling equipment.

7. The contractor's overhead and profit was 15 percent of the total capital cost and the contractor's contingency was 10 percent of the total capital cost.

Table 20 lists the estimated ozonation cost necessary to achieve the color standard of 10 units or less in non-nitrified secondary effluent and the California effluent coliform limit of 2.2 MPN per 100 ml. These costs are approximately 12 cents/1000 gallons and 6 cents/1000 gallons, respectively.

If pretreatment were employed, the California effluent coliform limit could be achieved at an ozonation cost of 4 cents/1000 gallons. Table 21 shows a summary of the ozonation costs with pretreatment. The most cost-effective pretreatment system appears to be Scheme C, carbon adsorption followed by ozonation. The estimated cost of providing sufficient ozonation and carbon filtration to achieve the California effluent coliform limit is approximately 14 cents/1000 gallons. An oxygen recycle system of 50 percent was assumed in the estimate.

TABLE 20. OZONATION COST WITH NO PRETREATMENT

Disinfection to 2.2 or less MPN/100 ml total coliform w/60 mg/l Ozone Dose	Color removal to 10 units w/12 mg/l Ozone Dose
12.2¢/1000 gal	3.9¢/1000 gal

* Effluent Source, Secondary Effluent

TABLE 21. OZONATION COST WITH PRETREATMENT

Alternate	1	2	3	4
Pretreatment A	15.9			
Pretreatment B		6.9		
Pretreatment C_1			10.4	
Pretreatment C_2				10.4
Ozone (@ 12 mg/l)	3.9			3.9
Ozone (@ 24 mg/l)			6.4	
Ozone (@ 48 mg/l)		10.4		
Total Cost (¢/1000 gal)	19.8	17.3	16.8	14.3

* Effluent Source, Secondary Effluent

APPENDIX A

MODIFIED VIRUS CONCENTRATION PROCEDURE

1. Membrane Adsorption

   a. Sample is pumped at 0.7 gal/min through a proportioning pump which adds dilute HCl and 0.01 M $AlCl_3$ to reach pH 3.5 and 0.0005M Al+++. Sample volume = 20 to 100 gallons.

   b. Acidified and aluminum amended sample is pumped through a K27 fiber-glass filter of porosity 3μ and 293 mm Cox filters of 1μ and 0.45μ porosities.

2. Elution

   Viruses are eluted from K27 and Cox filters by passing pH 11.5, 0.05M glycine through the filters in series until the pH of eluate leaving the filters is $\geq$11.0. Two or more liters of eluant are used. Eluant is immediately neutralized to pH 7.0 using pH 2, 0.05M glycine. Final eluant volume is approximately 4 liters.

3. Reconcentration

   a. Chemical Precipitation

      1. While mixing, add 0.5 M $AlCl_3$ to the 4 liters of eluate from the adsorbent filters to reach 0.003M Al+++. This lowers the pH of the solution to approximately 4 and creates floc.

      2. Add 1 M Na_2CO_3 to reach pH 7.0 while mixing.

      3. Allow floc to settle 20-25 minutes. Typical settled volume is 1000 ml. Discard supernate.

      4. Transfer floc to centrifuge bottles and centrifuge six minutes at 10,000 rpm.

      5. Combine centrifuge pellets and elute viruses from floc with pH 11.5, 0.05M glycine containing 0.1 percent Tween-80 and 0.05M EDTA. Mix with high speed mixer. Add 1 N NaOH while mixing to maintain pH 10. Contact time at pH 10 = 10 minutes. Volume of eluant used is 0.5 times the volume of centrifuged floc.

6. Centrifuge to sediment undissolved floc at 14,000 rpm for 10 minutes. Decant supernate which contains viruses and adjust to pH 7.0 with 1 N HCl while stirring.

7. Repeat elution with second identical volume of glycine and combine supernates. Final specimen volume ≈50 ml.

b. Alginate Filtration

1. Filter supernate from chemical precipitation at 70 psi through 47 mm diameter soluble alginate filter.*

2. Dissolve alginate portion of filter in 0.85 percent physiological sodium citrate. Final volume ≈5 ml.

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* Sartorious Corporation.

APPENDIX B

APPLIED OZONE DETERMINATION

Reagent

1. Potassium Iodide Solution (20 gm/l or 2% by wt)
2. Sulfuric Acid, 2N
3. Sodium Thiosulfate Solution, 0.1N-dissolve 24.8 grams $Na_2S_2O_2 \cdot 5H_2O$ in boiling water and dilute to 1 liter at room temperature.
4. Starch Indicator Solution

Procedure

1. Set-up apparatus as shown in Figure 1.
2. Place 400 ml of Reagent (1) in gas washing bottle.
3. Pass specified volume (0.1 ft) of sample through gas washing bottle. Volume of ozone sample can be determined from the wet test meter. Note temperature and barometric pressure of wet test meter.
4. Acidify sample solution with 10 ml of Reagent (2).
5. Titrate sample solution with Reagent (3) using Reagent (4) as an end-point indicator.

APPENDIX C

OZONE RESIDUAL DETERMINATION

Reagent

1. Postassium Iodide Crystals
2. Sodium-Azide-Alkali-Iodide Reagent-prepared by mixing 1 liter of sodium hydroxide and sodium iodide (135 gms) to 40 ml of sodium azide (10 gms).
3. Sulfuric Acid, 6N
4. Starch Solution, 1 percent
5. Sodium Thiosulfate Solution, 0.083N
6. Sodium Thiosulfate Solution, 0.0083N
7. Sodium Thiosulfate Solution, 0.00083N

Procedure

1. Rinse erlenmeyer sample flask with distilled water.
2. Add 0.1 gm of Reagent (1) to sample flask.
3. Collect 100 ml of sample in flask.
4. Add 1 ml of Reagent (2) to sample.
5. Acidify sample with Reagent (3) until acidic reaction and mix well.
6. Add 5 drops of Reagent (4) to sample and mix.
7. If dark-blue-black color appears, titrate with Reagent (5).

   Each drop is equivalent to 1 mg. O_3/l of sample

If pale-blue color appears, titrate with Reagent (6).

Each drop is equivalent to 0.1 mg. O_3/l of sample

If light-blue color appears, titrate with Reagent (7)

Each drop is equivalent to 0.01 mg. O_3/l of sample.

APPENDIX D

UNIT CONVERSIONS

UNIT	METRIC EQUIVALENT
1 pound (lb)	453.6 grams (g)
1 gallon (gal)	3.785 liters (l)
1 inch (in)	2.540 centimeters (cm)
1 foot (ft)	0.305 meters (m)
°F	1.8 (°C) + 32